

A HIGH INTENSITY GAMMA RADIATION  
SURVEY METER

—♦♦♦—  
JEROME HENRY KING, JR.

1951

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A HIGH INTENSITY GAMMA RADIATION SURVEY METER

by

LIEUTENANT COMMANDER JEROME HENRY KING, JR., U.S. NAVY

B.E., Yale University  
(1941)

SUBMITTED IN PARTIAL FULFILLMENT OF THE  
REQUIREMENTS FOR THE DEGREE OF  
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Signature of author .....  
Department of Physics, May 18, 1951

Verified by .....  
Thesis Supervisor

.....  
Chairman, Departmental Committee on Graduate Students

# A High Intensity Gamma Radiation Survey Meter

by

Lieutenant Commander Jerome Henry King, Jr., U.S. Navy

Submitted for the degree of Master of Science in the  
Department of Physics on May 18, 1951

## ABSTRACT

The possibility of attack by atomic weapons has created a widespread need for a rugged, portable gamma survey meter reading from 0.025 to 500 roentgens per hour. Such an instrument should be highly reliable, with long shelf and operating life. Two possible bases for such an instrument have been investigated.

A system using no batteries or other power-supply, in which a phosphor is viewed by a photo-voltaic cell of the barrier-layer type is shown to be too insensitive with presently available components to give meter indications in the radiation range of interest.

Visual observation of the luminescent response of a Zn-CdS phosphor is shown to permit detection of gamma radiation at less than 0.020 r/hr and measurement at less than 0.4 r/hr. The upper limit has not been explored but is shown to be above 100 r/hr. Two meter designs based on visual comparison of the brightness of a detector phosphor with that of a standard light source have been developed. One of these requires no power supply, the standard light source being a phosphor disc excited by a long-lived beta emitter, tests of which are described. The advantage in reliability of the device over an



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ABSTRACT

The possibility of attack by atomic weapons has created a widespread need for a rugged, portable gamma survey meter reading from 0.05 to 500 roentgens per hour. Such an instrument should be highly reliable, with long shelf and operating life. Two possible bases for such an instrument have been investigated.

A system using no batteries or other power-supply, in which a phosphor is viewed by a photo-voltaic cell of the barrier-layer type is shown to be too insensitive with presently available components to give meter indications in the radiation range of interest.

Visual observation of the luminescent response of a Cs<sub>2</sub> phosphor is shown to permit detection of gamma radiation at less than 0.010 r/hr and measurement at less than 0.4 r/hr. The upper limit has not been explored but is shown to be above 100 r/hr. Two meter designs based on visual comparison of the brightness of a detector phosphor with that of a standard light source have been developed. One of these requires no power supply, the standard light source being a phosphor also excited by a long-lived beta emitter, tests of which are described. The advantage in reliability of the device over an

electronic circuit is evident.

Measurements of brightness comparison at 0.8 r/hr showed standard deviations of 12% for each of two observers with 7% difference in the means of their readings. Dark adaptation of the observer, for a period varying inversely with radiation intensity, is required below about 15 r/hr.

Methods are described for preparing phosphor screens of any desired thickness by binding the phosphor powder in transparent plastics. In lucite, the greatest light yield under gamma excitation was obtained at  $1.0 \text{ gm/cm}^2$  of Zn-CdS, with an optimum phosphor to plastic weight ratio of 2.8:1. With polystyrene, the light yield of a given weight of phosphor in the optimum phosphor-plastic ratio is shown to be 30% higher than that of the same thickness of phosphor alone, a result of the relatively high index of refraction of the polystyrene. The light yield as a function of thickness of Zn-CdS and  $\text{Zn}_2\text{SiO}_4$  powder under gamma and beta excitation, and of various phosphor-plastic mixtures under gamma excitation are shown. For these measurements a procedure was devised to calibrate the response of a photomultiplier to the brightness of a luminescing phosphor in units of foot-lamberts.



electronic circuit is evident.

Measurements of brightness compared at 0.5 r/hr showed standard deviations of 1% for each of two observers with 7% difference in the means of their readings. Lack of variation of the observer, for a period varying inversely with radiation intensity, is required below about 1 r/hr.

Methods are described for preparing phosphor screens of any desired thickness by binding the phosphor powder in transparent plastics. In India, the greatest light yield under gamma excitation was obtained at 1.5 g/cm<sup>2</sup> of Zn-Cd<sub>2</sub>S<sub>2</sub> with an optimum phosphor to plastic weight ratio of 2.6:1. With polystyrene, the light yield of a given weight of phosphor in the optimum phosphor-plastic ratio is shown to be 30% higher than that of the same thickness of phosphor alone, a result of the relatively high index of refraction of the polystyrene. The light yield as a function of thickness of Zn-Cd<sub>2</sub>S<sub>2</sub> and Zn<sub>2</sub>SiO<sub>4</sub> powder under gamma and beta excitation, and of various phosphor-plastic mixtures under gamma excitation are shown. For these measurements a procedure was devised to calibrate the response of a photomultiplier to the brightness of a luminescing phosphor in units of foot-lamberts.



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1960-1961

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## CHAPTER 1

### NEED FOR A HIGH-INTENSITY GAMMA RADIATION SURVEY METER

The possibility of the use of atomic weapons against densely populated areas as well as strictly military targets has created a need for the wide-spread distribution of radiation dosage rate monitoring and survey instruments for use by radiological defense teams, and by individual persons, both civilian and military. Until very recently such instruments have been designed primarily for use by trained personnel under conditions such that personnel hazards due to failure of an instrument could be minimized by careful handling and maintenance, and by the provision of more than one monitor if necessary. Low cost and simplicity of operation have not been essential factors in the design of such instruments and, whether portable or laboratory types, they have in general been characterized by high sensitivity and the precision required for research purposes.

In this chapter we consider briefly the conditions under which individual persons and radiological defense teams might require instruments for measuring radiation, examine current civil defense specifications for such instruments, and mention the currently available instruments that might fall within the scope of these specifications.

## CHAPTER I

THE PROBLEM OF A HIGH-INTENSITY GAMMA RADIATION SOURCE

The possibility of the use of atomic weapons against densely populated areas as well as military targets has created a need for the wide-spread distribution of radiation source monitoring and survey instruments for use by radiological defense teams, and by individual persons, both civilian and military. Until very recently such instruments have been designed primarily for use by trained personnel under conditions such that personnel hazards due to failure of an instrument could be minimized by careful handling and maintenance, and by the provision of more than one monitor if necessary. Low cost and simplicity of operation have not been essential factors in the design of such instruments and, whether portable or laboratory type, they have in general been characterized by high sensitivity and the precision required for research purposes.

In this chapter we consider briefly the conditions under which individual persons and radiological defense teams might require instruments for measuring radiation, examine current civil defense specifications for such instruments, and mention the currently available instruments that might fall within the scope of these specifications.



### 1.1. Radiation after Atomic Weapon Attack.

At this writing, the most useful, if not the only available, source of unclassified information on the radiation to be expected after an atomic weapon attack is a publication, "The Effects of Atomic Weapons," (L1)<sup>1</sup> which reflects the experience obtained by the United States with the experimental and wartime nuclear explosions up to the beginning of 1950. We summarize some of the pertinent comments contained therein, quoting freely to avoid ambiguities.

Atomic weapons fall into two categories, explosives and the spread of radioactive contaminants (the latter is known as radiological warfare).

The effects of explosions vary depending on the relation of the burst to the surface of the ground or water, and this discussion is sub-divided accordingly. The figures quoted below apply to a "nominal" atomic bomb, equivalent to 20,000 tons of TNT, and we confine consideration to the residual radiation resulting from the weapon, excluding the initial burst of electro-magnetic and particle radiation which is substantially completed within one minute after the explosion. In general it can be said of the residual radiation that the personnel hazards arise primarily from gamma rays, and secondarily from beta-rays, the other forms of radiation

---

1. References are listed in Appendix A2.

1.1. Radiation after Atomic Bombing

At this writing, the most useful, if not the only available, source of detailed information on the radiation to be expected after an atomic weapon attack is a publication, "The Effects of Atomic Weapons," (11) which reflects the experience obtained by the United States with the experimental and civilian nuclear explosion up to the beginning of 1950. It summarizes some of the pertinent comments contained therein, pointing freely to avoid misinterpretation. Atomic weapons fall into two categories, equivalent to the spread of radioactive contamination (the latter is known as radiological warfare). The effects of explosions vary depending on the radiation of the burst to the surface of the ground or water, and this discussion is subdivided accordingly. The figures quoted below apply to a "nominal" atomic bomb, equivalent to 20,000 tons of TNT, and no cooling consideration is the residual radiation resulting from the weapon, including the initial burst of electro-magnetic and particle radiation which is substantially negligible within one minute after the explosion. In general it can be said that the residual radiation does not present hazards as serious as those from gamma rays, and especially from beta-rays, the other forms of radiation.

1.1.1. Radiation after Atomic Bombing



being present in negligible amounts in comparison. The energy of the residual radiation is not discussed in detail in the reference but the average energy is said to be 0.7 Mev.

(a) High air burst (above 500 feet):

"....if an atomic bomb is detonated at a high altitude, so as to cause maximum blast damage in a city, the hazard due to radioactivity on the ground after the explosion is small." (p. 269).

(b) Low air burst (below 500 feet):

Approximate radiation dosage rates were measured on the ground one hour after the first nuclear explosion at Alamogordo in 1945, where the burst occurred at a height of 100 feet. The dosage rate was 8,000 roentgens per hour at ground zero (the point directly under the burst), and fell off rapidly with (horizontal) distance from ground zero, to 10 r/hr at 1500 feet and to 0.3 r/hr, at 3000 feet. (p. 270).

"....after an air burst at low altitude an area, small compared with the damage area due to the bomb, near the explosion center would be uninhabitable because of the radiation hazard....It would probably be 6 hours or more before it would be safe to walk across the area...." (p. 270).

In addition to the residual radiation on the ground under the burst, separate consideration is given, in the case of low bursts, to "fall-out," that is, particles of dust carried upward

being present in negligible amounts in comparison. The energy of the residual radiation is not discussed in detail in the reference but the average energy is said to be 0.7

(a) High air burst (above 500 feet):

"...If an atomic bomb is detonated at a high altitude, so as to cause maximum blast damage in a city, the hazard due to residual activity on the ground after the explosion is small." (p. 291)

(b) Low air burst (below 500 feet):

Approximate residual dosage rates were measured on the ground one hour after the first nuclear explosion at Alamogordo in 1945, where the burst occurred at a height of 500 feet. The dosage rate was 0.0002 roentgens per hour at ground level (the point directly under the burst), and fell off rapidly with (horizontal) distance from ground zero, so is 1/hr at 1500 feet and 0.00002 roentgens per hour at 3000 feet. (p. 292)

"...After an air burst at low altitude an area, small compared with the damage area due to the bomb, near the explosion center would be uninhabitable because of the radiation hazard... It would probably be 6 hours or more before it would be safe to walk across the area..." (p. 292)

In addition to the residual radiation on the ground under the burst, separate consideration is given in the case of low bursts, to "fall-out," that is, particles of dust carried upward



by the hot air current around the burst which later fall to earth elsewhere carrying radio-activity. It is stated that,

"The fall-out in the case of a low air burst might be an inconvenience but it would not, in general, represent a real danger. It would probably rarely be enough to prevent passage across an area, although it might necessitate suspension of operations for a few days within the area." (p. 274).

(c) Surface Explosion:

"It is reasonably certain that the contamination due to neutron-induced activity in the vicinity of the explosion would be very high....airborne activity, which could produce a significant fall-out, might constitute a serious hazard in areas directly downwind at some distance from the explosion." (pp. 274, 275).

(d) Underwater Burst:

"Of the types of atomic explosion the underwater test at Bikini produced by far the greatest degree of radioactive contamination... The extent and degree of contamination will probably vary markedly with the conditions, such as.... depth of the burst, meteorological conditions.... and topography." (pp. 276-277).

Of the total radiation dosage at a given distance from surface zero, about 90% may be expected within 30 minutes of the explosion. Integrated dosage contours, based on the Bikini underwater burst, where a 5 m.p.h. wind was blowing, place the 100 roentgen (total dose) contour 3.3 miles downwind from the burst, and the 400 r contour 2.2 miles from the burst. In

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"Of the types of atomic explosion the under-  
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The extent and degree of contamination will  
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underwater burst, where a 2 m.t.h. yield was  
blowing, show the 100 roentgen (total dose)  
contour 1.3 miles downwind from the burst, and  
the 400 r contour 2.5 miles from the burst. In



other directions these contours were correspondingly closer to surface zero.

Approximate dosage rates one hour after the burst, downwind, were 50 r/hr at 2 miles, 10 r/hr at 3 miles and at 5 miles the radiation was negligible. A different wind velocity or a shift in the wind shortly after the explosion could of course alter the results considerably.

(e) Radiological Warfare:

"On the whole it may be concluded that if radiological warfare is used as a weapon, it will be in the form of emitters of penetrating gamma radiation for which protective clothing and gas masks would be ineffective... However, it would appear to be a difficult matter to lay down such a concentration of gamma emitters over a large area as would cause serious injury from a short exposure." (p.288)

1.2. Monitoring Equipment for Emergency Workers.

While the foregoing comments establish the almost self-evident fact that an atomic attack on a city would result in radioactive contamination affecting a large number of people, they do not readily lead to the particular limits of sensitivity and other specifications for an instrument intended for emergency use.

For guidance in these matters we turn to a recent publication of the Federal Civil Defense Administration (F2) which sets forth specifications for radiological monitoring instruments for use in general civil defense operations. These specifications were compiled by a committee, including repre-





representatives from all interested Government agencies, which

"....determined that two types of radiological monitoring instruments are required for gamma ray detection:

- (1) A high-intensity instrument for area survey operation immediately following an atomic attack. These instruments must have an upper range of 500 roentgens per hour.
- (2) A low-intensity instrument for special long-range survey work in the weeks following an attack..... The range of these instruments need not exceed 500 milliroentgens per hour.

"The committee has determined that while certain instruments now available would be suitable for the low-intensity radiation measurement in the weeks following a disaster, no instrument suitable for civil-defense high-intensity survey work has yet been developed."

The low-intensity instrument<sup>2</sup> currently recommended by the Federal Civil Defense Administration is an ionization-chamber type, portable, battery-powered device having five ranges of full-scale readings 5, 50, 500, 5000 and 50,000 milliroentgens per hour, detecting gamma radiation of energy 80 Kev up to 1.5 Mev. Specified precision is  $\pm 15\%$  (of the  $4/5$  full scale reading). It meets military requirements for ruggedness, resistance to temperature, humidity and pressure changes. Battery life provides 1000 hours of continuous operation and a shelf-life of about 1 year at 70°F.

In the absence of suitable high-intensity instruments for civil defense purposes, the committee drew "Tentative

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2. Type AM/PDR-T-1, manufactured by Tracerlab, Inc. and Kelley-Koett Mfg. Co.

contacting from all interested Government agencies, which  
".....determined that the types of radiological mani-  
festing instruments are required for gamma ray de-  
tection

- (1) A high-intensity instrument for area survey  
operation immediately following an atomic  
attack. These instruments must have an up-  
per range of 500 roentgens per hour.
- (2) A low-intensity instrument for special long-  
range survey work in the weeks following an  
attack..... The range of these instruments  
need not exceed 500 milliroentgens per hour.

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struments now available would be suitable for the  
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Specifications for a Civil Defense High-Intensity Radiation Survey Meter," published by the Federal Civil Defense Administration in the same report (F2). The specifications "establish performance requirements for a small, lightweight, rugged field instrument for measuring gamma radiation which may result from atomic disaster. The instrument will be used by relatively inexperienced personnel and should provide ease of operation, maximum operating life and require a minimum of maintenance." These specifications, then, provide the best currently available guide to the characteristics of an instrument for emergency use and they will be briefly outlined.

The device may be based on any practicable detection principle and must respond to gamma radiation of 0.08 to 1.5 Mev energy, over the range 0.025 to 500 roentgens per hour, reading correctly within  $\pm 30\%$  at 5, 50, and 500 r/hr. An integral calibration device is to be provided to check performance at one scale reading. Battery life is to provide 25 hours of continuous operation, and overall life except batteries must be at least 500 hours at 500 r/hr. There are in addition strict requirements to cover various operating conditions, as temperature, humidity, corrosion, immersion and vibration effects. The instrument is to be portable, having a weight of less than five pounds and a volume of less than 100 cubic inches. Various requirements on circuit stability, internal construction and external features are also specified.

Specifications for a Civil Defense High-Intensity Radiation Survey Meter, "published by the Federal Civil Defense Administration in the same report (VI). The specifications "contain" high performance requirements for a small, lightweight, rugged field instrument for measuring gamma radiation which may be used by relatively inexperienced personnel and which provides ease of operation, maximum operating life and requires a minimum of maintenance." These specifications, then, provide the best currently available guide to the characteristics of an instrument for emergency use and they will be briefly outlined. The device may be based on any practically detectable principle and must respond to gamma radiation of 0.05 to 1.5 Mr energy, over the range 0.015 to 500 röntgens per hour, reading correctly within  $\pm 30\%$  at 2, 50, and 500 r/hr. An integral calibration device is to be provided to check performance at one scale reading. Battery life is to provide 25 hours of continuous operation, and overall life except batteries must be at least 500 hours at 500 r/hr. There are in addition strict requirements to cover various operating conditions, as temperature, humidity, corrosion, immersion and vibration effects. The instrument is to be portable, having a weight of less than five pounds and a volume of less than 100 cubic inches. Various requirements on circuit stability, internal construction and external features are also specified.



Because of the relatively recent publication of these specifications, it is doubtful that any currently available radiation meter has been designed specifically to meet them. Two devices whose sensitivity range may possibly be extended to meet the above specifications have become available in recent months and will be described briefly.

LeVine and DiGiovanni (16) have described a compact hand-held instrument detecting gamma rays by a Geiger-Muller tube using 700 volts provided by a novel vibration circuit operating from two small (Type D) dry cells. Two models have been designed, one covering the range 0.2 to 500 r/hr, the other about 0.02 to 5 r/hr. The unit cost, for parts only, of either of these is \$14.50 if 100,000 are to be manufactured. The authors state that modifications can be made to meet the above specifications.

Another recent instrument, the "Pocket Radiac" (T1) is an ionization chamber type reading 0 to 25 r/hr on a logarithmic scale, with stated accuracy of  $\pm 25\%$  at any reading. The instrument responds to gamma rays of greater than 0.1 Mev energy and to beta-rays of over 1.0 Mev. Operating life is 85 hours, from two hearing-aid type batteries. A model reading up to 500 r/hr is in preparation. The present model is about the size of a man's hand. Cost is \$49.50 in small quantity.

These devices are believed to be the leading representa-

Because of the relatively recent production of these  
specifications, it is doubtful that any currently available  
radiation meter has been designed specifically to meet them.  
Two devices whose sensitivity ranges may possibly be extended  
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cent months and will be described briefly.

Levine and Lichtenstam (16) have described a compact  
hand-held instrument detecting gamma rays by a Geiger-Müller  
tube using 700 volts provided by a novel vibration circuit  
operating from two small (Type D) dry cells. Two models  
have been designed, one covering the range 0.1 to 500 r/hr.  
the other about 0.01 to 5 r/hr. The unit cost, for parts  
only, of either of these is \$11.50 to 100,000 are to be manu-  
factured. The authors state that modifications can be made  
to meet the above specifications.

Another recent instrument, the "Pocket Radiac" (17)  
is an ionization chamber type reading 0 to 25 r/hr on a  
logarithmic scale, with stated accuracy of  $\pm 25\%$  at any  
reading. The instrument responds to gamma rays of greater  
than 0.1 Mev energy and to beta-rays of over 1.0 Mev. OP-  
erating life is 65 hours. From two hearing-aid type batteries.  
A model reading up to 500 r/hr is in preparation. The pre-  
sent model is about the size of a man's hand. Cost is \$49.50  
in small quantity.

These devices are believed to be the leading representa-



tives of the sort of instrument contemplated by the specifications quoted above. A number of other types of gamma-ray detectors have been mentioned as potentially useful after an atomic explosion, for measuring the integrated dose received by an individual. These include pocket dosimeters of the electroscope or ionization chamber type, photographic film badges, and recently a silver-activated phosphate glass which fluoresces under ultra-violet light in proportion to the total gamma radiation to which it has been subjected. All of these are quite simple and rugged, but require auxiliary apparatus for either reading or re-charging (where applicable) or both. Though a measure of the dosage rate can be obtained with all of them by timing the exposure of the device, their use for this purpose in the field is subject to the principal objection that the information so obtained applies to the past, not the present, and that careful shielding is required to maintain the usefulness of any reserve stock of such devices in the presence of radiation.

We conclude from this brief survey that in spite of the many varieties of gamma-ray measuring instruments in existence, there remains an unfilled need for a wide-range gamma radiation survey meter of simple and rugged characteristics. It is the purpose of this paper to describe some initial investigations of two possible bases for such a device.

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trometer noted above. A number of other types of spec-  
trometer have been mentioned as potentially useful  
after an atomic explosion, for measuring the intensity  
of the radiation by an individual. These include photo-  
graphic film badges, and recently a silver-sulfide photo-  
graphic glass which fluoresces under ultra-violet light in  
proportion to the total gamma radiation to which it has been  
subjected. All of these are quite simple and rugged, and  
require auxiliary apparatus for either reading or re-shaping  
(where applicable) or both. Though a measure of the damage  
can be obtained with all of them by taking the exposure  
of the device, their use for this purpose in the field is  
subject to the principal objection that the information so  
obtained applies to the past, not the present, and that  
external shielding is required to maintain the usefulness of  
any remote look of such devices in the presence of radia-  
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We conclude from this brief survey that in spite of the  
many varieties of gamma-ray measuring instruments in existence,  
there remains an unfulfilled need for a wide-range gamma radia-  
tion survey meter of simple and rugged construction. It  
is the purpose of this paper to describe some initial investi-  
gations of two possible means for such a device.



## CHAPTER 2

### PHOSPHOR VIEWED BY PHOTO-VOLTAIC CELL

#### 2.1. Introduction.

In the search for a principle upon which an instrument of the sort described in Section 1.2 might be based, attention was directed first to the use of a simple photo-voltaic cell, of the barrier-layer type.<sup>1</sup> The cell was to view a phosphor crystal excited to luminescence by gamma rays or other energetic radiation and the sensitive surface of the cell would convert the light into an electric current, measured by a micro-ammeter. Preliminary calculations, reproduced below, indicated that the maximum current obtainable would be quite small, but nevertheless it seemed advisable to experiment with this principle to an extent sufficient to determine the possible sensitivity of such a device made with currently available components. It is apparent that, should sufficient sensitivity be achieved, a device of this nature would be extremely simple, readily manufactured, and would have an indefinitely long shelf-life, since no power supply would be required.

#### 2.2. Choice of Photo-Voltaic Cell.

Barrier-layer photo-voltaic cells now commercially

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1. The use of a photo-voltaic cell for this purpose was first suggested to the author by Professor Clark Goodman.



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1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2033, 2034, 2035, 2036, 2037, 2038, 2039, 2040, 2041, 2042, 2043, 2044, 2045, 2046, 2047, 2048, 2049, 2050, 2051, 2052, 2053, 2054, 2055, 2056, 2057, 2058, 2059, 2060, 2061, 2062, 2063, 2064, 2065, 2066, 2067, 2068, 2069, 2070, 2071, 2072, 2073, 2074, 2075, 2076, 2077, 2078, 2079, 2080, 2081, 2082, 2083, 2084, 2085, 2086, 2087, 2088, 2089, 2090, 2091, 2092, 2093, 2094, 2095, 2096, 2097, 2098, 2099, 2100, 2101, 2102, 2103, 2104, 2105, 2106, 2107, 2108, 2109, 2110, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2120, 2121, 2122, 2123, 2124, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2132, 2133, 2134, 2135, 2136, 2137, 2138, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2150, 2151, 2152, 2153, 2154, 2155, 2156, 2157, 2158, 2159, 2160, 2161, 2162, 2163, 2164, 2165, 2166, 2167, 2168, 2169, 2170, 2171, 2172, 2173, 2174, 2175, 2176, 2177, 2178, 2179, 2180, 2181, 2182, 2183, 2184, 2185, 2186, 2187, 2188, 2189, 2190, 2191, 2192, 2193, 2194, 2195, 2196, 2197, 2198, 2199, 2200, 2201, 2202, 2203, 2204, 2205, 2206, 2207, 2208, 2209, 2210, 2211, 2212, 2213, 2214, 2215, 2216, 2217, 2218, 2219, 2220, 2221, 2222, 2223, 2224, 2225, 2226, 2227, 2228, 2229, 2230, 2231, 2232, 2233, 2234, 2235, 2236, 2237, 2238, 2239, 2240, 2241, 2242, 2243, 2244, 2245, 2246, 2247, 2248, 2249, 2250, 2251, 2252, 2253, 2254, 2255, 2256, 2257, 2258, 2259, 2260, 2261, 2262, 2263, 2264, 2265, 2266, 2267, 2268, 2269, 2270, 2271, 2272, 2273, 2274, 2275, 2276, 2277, 2278, 2279, 2280, 2281, 2282, 2283, 2284, 2285, 2286, 2287, 2288, 2289, 2290, 2291, 2292, 2293, 2294, 2295, 2296, 2297, 2298, 2299, 2300, 2301, 2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309, 2310, 2311, 2312, 2313, 2314, 2315, 2316, 2317, 2318, 2319, 2320, 2321, 2322, 2323, 2324, 2325, 2326, 2327, 2328, 2329, 2330, 2331, 2332, 2333, 2334, 2335, 2336, 2337, 2338, 2339, 2340, 2341, 2342, 2343, 2344, 2345, 2346, 2347, 2348, 2349, 2350, 2351, 2352, 2353, 2354, 2355, 2356, 2357, 2358, 2359, 2360, 2361, 2362, 2363, 2364, 2365, 2366, 2367, 2368, 2369, 2370, 2371, 2372, 2373, 2374, 2375, 2376, 2377, 2378, 2379, 2380, 2381, 2382, 2383, 2384, 2385, 2386, 2387, 2388, 2389, 2390, 2391, 2392, 2393, 2394, 2395, 2396, 2397, 2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405, 2406, 2407, 2408, 2409, 2410, 2411, 2412, 2413, 2414, 2415, 2416, 2417, 2418, 2419, 2420, 2421, 2422, 2423, 2424, 2425, 2426, 2427, 2428, 2429, 2430, 2431, 2432, 2433, 2434, 2435, 2436, 2437, 2438, 2439, 2440, 2441, 2442, 2443, 2444, 2445, 2446, 2447, 2448, 2449, 2450, 2451, 2452, 2453, 2454, 2455, 2456, 2457, 2458, 2459, 2460, 2461, 2462, 2463, 2464, 2465, 2466, 2467, 2468, 2469, 2470, 2471, 2472, 2473, 2474, 2475, 2476, 2477, 2478, 2479, 2480, 2481, 2482, 2483, 2484, 2485, 2486, 2487, 2488, 2489, 2490, 2491, 2492, 2493, 2494, 2495, 2496, 2497, 2498, 2499, 2500, 2501, 2502, 2503, 2504, 2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512, 2513, 2514, 2515, 2516, 2517, 2518, 2519, 2520, 2521, 2522, 2523, 2524, 2525, 2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534, 2535, 2536, 2537, 2538, 2539, 2540, 2541, 2542, 2543, 2544, 2545, 2546, 2547, 2548, 2549, 2550, 2551, 2552, 2553, 2554, 2555, 2556, 2557, 2558, 2559, 2560, 2561, 2562, 2563, 2564, 2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574, 2575, 2576, 2577, 2578, 2579, 2580, 2581, 2582, 2583, 2584, 2585, 2586, 2587, 2588, 2589, 2590, 2591, 2592, 2593, 2594, 2595, 2596, 2597, 2598, 2599, 2600, 2601, 2602, 2603, 2604, 2605, 2606, 2607, 2608, 2609, 2610, 2611, 2612, 2613, 2614, 2615, 2616, 2617, 2618, 2619, 2620, 2621, 2622, 2623, 2624, 2625, 2626, 2627, 2628, 2629, 2630, 2631, 2632, 2633, 2634, 2635, 2636, 2637, 2638, 2639, 2640, 2641, 2642, 2643, 2644, 2645, 2646, 2647, 2648, 2649, 2650, 2651, 2652, 2653, 2654, 2655, 2656, 2657, 2658, 2659, 2660, 2661, 2662, 2663, 2664, 2665, 2666, 2667, 2668, 2669, 2670, 2671, 2672, 2673, 2674, 2675, 2676, 2677, 2678, 26

and the other two are in the same position as the first two.

[illegible]

will cause the growth of the  $\beta$  phase without causing the growth of the  $\alpha$  phase.

WOLFE HILL AT THE BATTLE OF 1806

Received 20 January 1993; accepted 10 April 1993

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112, also as power will be required

0.510 0.500 0.490 0.480 0.470 0.460 0.450 0.440 0.430 0.420 0.410 0.400

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Use not of a photo-elastic cell for this purpose was

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available are practically all of the selenium type (21), consisting of a thin layer of crystalline selenium on an iron base, covered with a thin sputtered metal electrode. Selenium is thought to be a defect semi-conductor with holes in its highest filled energy band (21). In contact with iron, of lower work function, some of the holes are filled by electrons migrating across the interface from iron to selenium, setting up a field across the boundary region which forms the barrier layer. In this condition, electrons excited by incident light may rise to the empty conduction band. In the interior of the semi-conductor, such electrons have a short lifetime, as they fall into the holes of the highest filled energy band, and no current will flow. In the region of the barrier layer, however, these holes are filled by the electrons which migrated from iron. Hence electrons in the conduction band have a longer lifetime during which they are urged by the field toward the iron, creating a current. Under moderate illumination, the open-circuit potential difference between the iron base and the top electrode is of the order of 0.2 volts, rising to a maximum of about 0.55 volts at very high illumination levels (V1).

Inspection of manufacturers' literature indicates that the performance characteristics of photo-voltaic cells





vary but little from one manufacturer to the next. Some of the characteristics of a typical General Electric cell of 1.1 in.<sup>2</sup> sensitive surface are shown in Figures 2.2-1, 2, and 3, and an equivalent circuit representing conventional cells is given in Figure 2.2-4. Major characteristics of interest here are:

- (a) Spectral sensitivity maximum nearly coincides with the wavelength of maximum sensitivity of the human eye (Figure 2.2-1).
- (b) With small external resistance loads, current output is proportional to the illumination (Figure 2.2-2).
- (c) Internal resistance (and hence optimum external load) is a function of illumination (Figure 2.2-3).
- (d) Short-circuit current is nearly proportional to sensitive area. Open circuit voltage is practically independent of area (21).
- (e) Special attention to the details of manufacture may produce cells with current response about 10% higher than the average (21).
- (f) Representative values of the equivalent circuit elements of Figure 2.2-4 are (21):

$$C \approx 0.1 \text{ to } 0.5 \text{ mfd.}$$

very low level from the microphone to the ear, and of the characteristics of a typical human ear of 1.1 in. <sup>2</sup> sensitive surface are shown in Figure 2.1-1.  $\bar{M}$ , and  $\bar{J}$ , and an equivalent circuit diagram of the ear is given in Figure 2.1-2. The characteristic of interest here are:

(a) Spectral sensitivity which may be calculated with the knowledge of human sensitivity of the human ear (Figure 2.1-1).

(b) The small external resistance loads, current output is proportional to the illumination (Figure 2.1-2).

(c) Internal resistance (and load) system when ear load is a function of illumination (Figure 2.1-3).

(d) Short-circuit current is only proportional to sensitive area. Open circuit voltage is proportional independent of area (2.1-4).

(e) Spectral sensitivity in the details of ear response may produce cells with various responses about 10% above and below average (2.1-5).

(f) Representative values of the spectral output elements at Figure 2.1-2 are (2.1-6)

$$R \approx 0.1 \text{ to } 0.5 \text{ m}\Omega$$

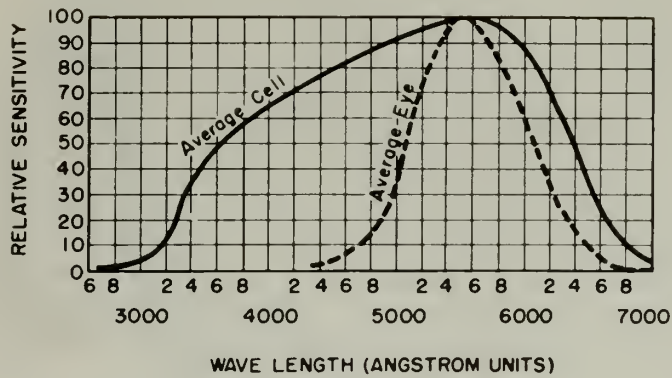


Figure 2.2-1. Photocell spectral sensitivity for constant energy at each wavelength. (From Ref. G1.)

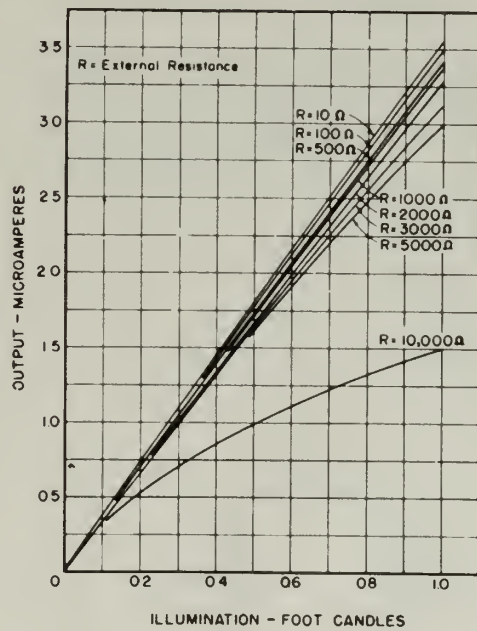


Figure 2.2-2. Photocell current vs. illumination (tungsten, 2700°K) (From Ref. G1.)





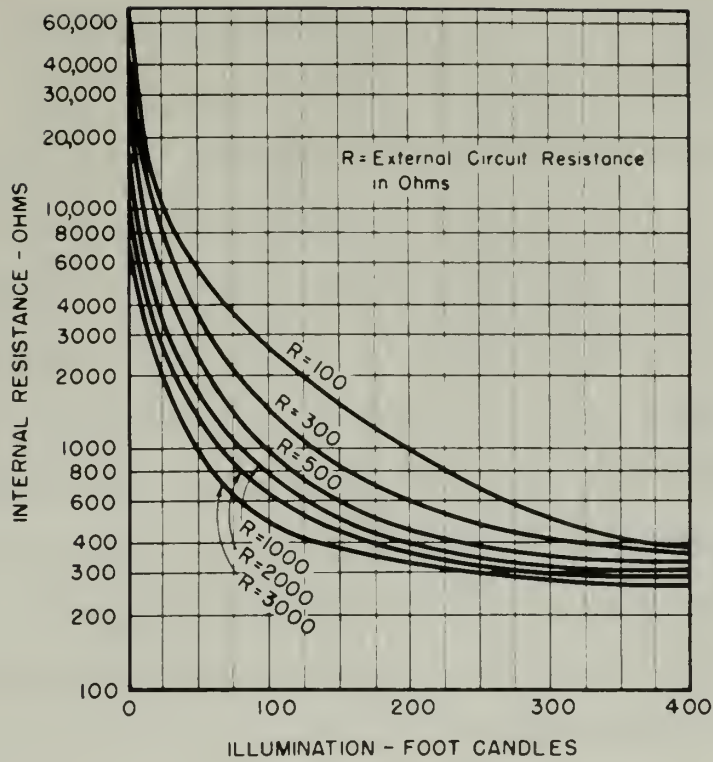


Figure 2.2-3. Photocell internal resistance vs. illumination (tungsten, 2700°K). (From Ref. G1.)

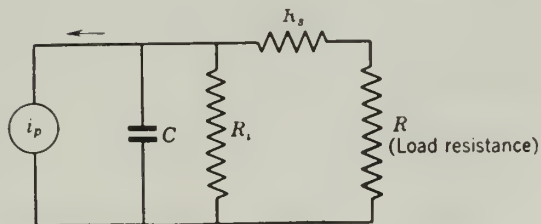
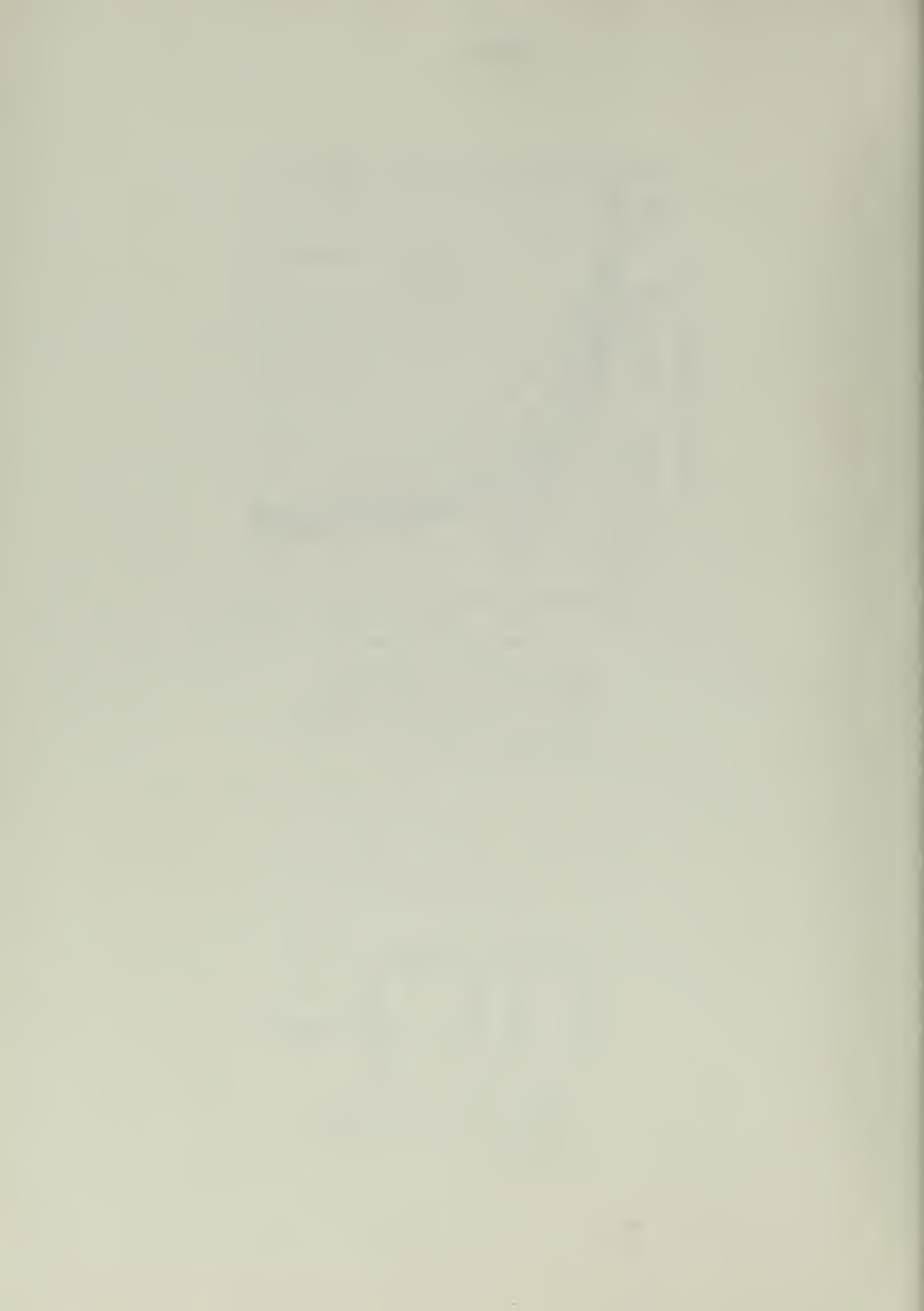


Figure 2.2-4. Photocell equivalent circuit. (From Ref. Z1.)





$R_s \approx 50 \text{ ohms}$

$R_i$  = a function of illumination and external circuit resistance as shown in Figure 2.2-3.

With these characteristics in mind, two specially made photocells with sensitive areas of  $15 \text{ cm}^2$  were obtained (from General Electric Company) for use in the experiments described below. For these cells the characteristics as given in Figures 2.2-1, 2, and 3 represent minimum expected performance. (If small external loads are used, corresponding to short-circuit conditions, the currents shown in Figure 2.2-2 should be multiplied by the ratio of the areas ( $\frac{2.3}{1.1} = 2.1$ ) to give the expected current.)

### 2.3. Choice of Luminescent Material.

Having selected a photo-voltaic cell, we sought a luminescent material (phosphor) with maximum sensitivity to gamma radiation. In addition to availability and cost, three major factors were considered:

- (a) The material chosen should be of high atomic number, so that it will absorb as much energy as possible from the gamma radiation.
- (b) The material should emit as visible light a large fraction of the energy absorbed.
- (c) The emitted light should fall as nearly as

as 50 ohms  
 = a function of illumination and ex-  
 ternal circuit resistance as shown

in Figure 2.3-3.

With these characteristics in mind, two specially made  
 photocells with sensitive areas of  $1\frac{1}{2}$  cm<sup>2</sup> were obtained  
 (from General Electric Company) for use in the experiments  
 described below. Two glass cells for photovoltages are  
 given in Figures 2.3-1, 2, and 3 representing minimum expected  
 performance. (If small external loads are used, counter-  
 ing to short-circuit conditions, the currents shown in Fig-  
 ure 2.3-2 should be multiplied by the ratio of the areas  
 ( $\frac{2.1}{1.1} = 2.1$ ) to give the expected currents.)

## 2.4 Choice of luminous material

Having selected a photo-voltaic cell, we sought a  
 luminous material (phosphor) with maximum sensitivity to  
 gamma radiation. In addition to sensitivity and cost, these  
 major factors were considered:

- (a) The material chosen should be of high atomic  
 number, so that it will convert as much energy  
 as possible from the gamma radiation.
- (b) The material should emit as visible light a  
 large fraction of the energy absorbed.
- (c) The emitted light should fall as nearly as

possible in the region of maximum photocell sensitivity.

- (d) Since the response of photo-voltaic cells decreases with increasing frequency, rapid decay of the emitted light pulses would be undesirable.

Kallman and co-workers (21) have made an extensive study of the absolute energy yield of various luminescent materials excited with alpha particles, gamma rays, and weak x-rays. Their results show that, in general, the inorganic phosphors emit as visible light a greater fraction of the energy absorbed than do the organic luminescent materials. Of the inorganic materials they tested under gamma radiation from radium and its decay products, the two most suitable for the present purpose are copper-activated zinc sulfide (denoted  $\text{ZnS}(\text{Cu})$ ) with an efficiency of 22%, and copper-activated zinc-cadmium sulfide ( $\text{Zn-CdS}(\text{Cu})$ ), with an efficiency of 18%. These efficiency data represent the ratio of energy emitted as light to the (radium) gamma radiation energy absorbed by a thin layer of phosphor. The efficiencies of several sulfide phosphors, including these two, have been shown (24), (21), to be a function of the intensity of the exciting radiation, and of temperature. For this reason Kallman (22) has stated, referring to the efficiencies cited above, that they may be in error by as much as 1/5 to 1/3.



possible in the region of certain physical

similarity.

(d) Since the spectrum of the observed light is

practically continuous, it is likely that the

of the emitted light is not in the visible

region.

The results of the present study (a) have made an extensive

study of the observed energy field of various ionospheric

layers, and the results are given in the following table.

Table. The results of the present study of the ionospheric

layers, and the results are given in the following table.

Energy absorbed in the ionosphere under various conditions.

of the ionosphere under various conditions.

from the region and the energy produced, the two most

important for the present purpose are the energy produced and the

energy absorbed in the ionosphere under various conditions.

per-unit area of the ionosphere under various conditions.

of the ionosphere under various conditions.

of energy absorbed in the ionosphere under various conditions.

energy absorbed in the ionosphere under various conditions.

of energy absorbed in the ionosphere under various conditions.

of energy absorbed in the ionosphere under various conditions.

of energy absorbed in the ionosphere under various conditions.

of energy absorbed in the ionosphere under various conditions.

of energy absorbed in the ionosphere under various conditions.

though the relative values are correct.

Both of these phosphors emit light in a fairly broad spectrum with the maximum in both cases falling near the wavelength of maximum sensitivity of the selenium barrier-layer photo-voltaic cell. If the relative spectral distribution,  $J_\lambda$ , of the energy emitted by a phosphor is known as a function of wavelength, then the average current sensitivity,  $S$ , of a photo-sensitive surface to this distribution can be calculated as:

$$S = \frac{\int_0^\infty J_\lambda S_\lambda d\lambda}{\int_0^\infty J_\lambda d\lambda} \leq 1,$$

where  $S_\lambda$  represents the current response of the photo-sensitive surface at wavelength  $\lambda$ , relative to the current output  $I_0$  (amperes per unit incident energy) at the wavelength of maximum sensitivity.  $S$  is thus a figure of merit for various combinations of photocell surfaces and phosphors. Calculations of  $S$  have been made for the two phosphors mentioned above as being most suitable, based on the response curve  $S_\lambda$  for the General Electric cell (Figure 2.2-1). For  $\text{ZnS}(\text{Cu})$ , the spectral emission curve of a very efficient phosphor prepared by Tube (23) was employed, while for  $\text{ZnS}(\text{Ag})$ , a spectral emission curve, Figure 3.2-1, for one

through the relative values of the observed  
 loss of mass processes with light in a fairly broad  
 spectrum with the variation in both phases (solid and gas)  
 wavelength of maximum sensitivity of the solution method  
 later photo-voltaic cells. It can relative spectral distri-  
 bution,  $\lambda$ , of the energy emitted by a photodiode is found  
 on a transition of wavelength, from the average constant mean-  
 value,  $\lambda$ , of a photo-sensitive surface to this distribution  
 and be calculated as:

$$I = \frac{I_0 \lambda^2}{\lambda^2 + \lambda_0^2}$$

where  $I$  represents the current response of the photo-  
 sensitive surface at wavelength  $\lambda$  relative to the average  
 value  $I_0$  (current per unit surface area) at the wave-  
 length of maximum sensitivity. It is seen a figure of merit  
 for various combinations of photodiode surface and wavelength  
 calculations of a few cases will show the two photodiode sur-  
 faces above we have used will give a good result in the response  
 curve of the two photodiode surfaces will (Figure 2-3-1). The  
 results of the spectral calculations show as a very significant  
 difference between the two (17) and (18) are significant, which for the  
 calculation, a spectral emission curve, Figure 2-3-1, for the  
 surface, which will give a good result in the response



of the plastic-phosphor discs described in Chapter 4 was used. The ordinates of these curves represent, in arbitrary units, energy emitted per unit energy absorbed, per unit wavelength, under excitation by ultra-violet radiation. Since the emission spectrum of a given phosphor is constant, or nearly so, under various modes (alpha, beta, gamma, ultra-violet) of excitation (L3), and (K1), these data may be used for the present problem involving gamma-ray excitation.

The figures obtained for S by graphical integration are:

$$\text{ZnS(Cu)} : S = 0.89$$

$$\text{Zn-CdS(Cu)} : S = 0.95$$

The time rate of decay of light pulses from phosphors appears to be a sensitive function of constitution and method of preparation of the phosphor. Much conflicting data are found in the literature on this topic. However there is no doubt that ZnS(Cu) and Zn-CdS(Cu) emit light in very long pulses compared to the short (of the order of  $10^{-7}$  seconds) pulses of the organic phosphors, and the zinc and cadmium sulfides are for this reason almost invariably used where long persistence of luminescence is desired, e.g., in slow-moving oscillography (R3), (L2). The phosphorescent decay of a Zn-CdS(Cu) phosphor material used in the present experiments

of the phosphor lines described in Section 4 was used. The ordinates of these curves represent, in arbitrary units, energy emitted per unit energy absorbed, per unit wavelength, under excitation by ultra-violet radiation. Since the emission spectrum of a given phosphor is constant, or nearly so, under various modes (ultra-violet, gamma, ultra-violet) of excitation (13), and (14), these data may be used for the present problem involving gamma-ray excitation.

The figures obtained for B by graphical integration

are:

$$\begin{aligned} \text{Zn(Cu)} : B &= 0.79 \\ \text{Zn-Cd(Cu)} : B &= 0.92 \end{aligned}$$

The time rate of decay of light pulses from phosphors appears to be a sensitive function of excitation and method of preparation of the phosphor. When oscillating data are found in the literature on this topic, however, there is no doubt that Zn(Cu) and Zn-Cd(Cu) emit light in very long pulses compared to the short (of the order of  $10^{-7}$  seconds) pulses of the organic phosphors, and the time and volume studies are for this reason almost invariably used where long persistence of luminescence is desired, e.g., in slow moving oscillography (15), (16). The phosphorescent decay of a Zn-Cd(Cu) phosphor material used in the present experiments



persisted for more than 20 minutes after excitation was removed.

To summarize,  $\text{ZnS}(\text{Cu})$  and  $\text{Zn-CdS}(\text{Cu})$  appear to be suitable phosphors for the present application, as they have reasonably high gamma-ray absorption characteristics, are among the most efficient energy converters, emit light in a band favoring the selenium photo-sensitive surface, and emit pulses of long duration which avoid the poor high-frequency response of barrier-layer cells.

#### 2.4. Estimate of Sensitivity.

Attempts to calculate the expected sensitivity of a simple phosphor-photovoltaic cell-ammeter arrangement suffer from the scarcity of data on the performance of photovoltaic cells at the very low levels of illumination expected from the phosphor under moderate gamma irradiation. The data in Figure 2.2-2 are the best available on commercial cells at illumination levels below 1 foot-candle (1 lumen/ft.<sup>2</sup>). However, the lowest portion of these curves, below about 0.2 foot-candles, is an extrapolation (W1). On the basis of the brief discussion of the theory of the photovoltaic cell given above, a linear relationship between illumination and current response, passing through the origin of coordinates, seems plausible. If the illumination is small, so that the field at the selenium-iron interface is not disturbed by a large current flow, then a fixed fraction



persisted for more than 20 minutes after excitation was removed.

To summarize,  $\text{InSb(Cu)}$  and  $\text{GaAs(Cu)}$  appear to be suitable phosphors for the present application, as they have reasonably high quantum efficiency characteristics, are among the most efficient energy converters, emit light in a band favorable for selenium photo-sensitive surfaces, and emit light of long duration which avoids the poor high-frequency response of barrier-layer cells.

#### 2.4. Features of Sensitivity

Attempts to calculate the expected sensitivity of a simple phosphor-photocell self-excited arrangement suffer from the scarcity of data on the performance of photo-voltaic cells at the very low levels of illumination expected from the phosphor under moderate current excitation. The data in Figures 2.2-2 are the best available on commercial cells at illumination levels below 1 foot-candle (1 lumen/ $\text{ft}^2$ ). However, the lowest portion of these curves, below about 0.2 foot-candles, is an extrapolation (W1). On the basis of the brief discussion of the theory of the photo-voltaic cell given above, a linear relationship between illumination and output is expected, provided the origin of coordinates, where applicable. If the illumination is so low that the field at the selenium-surface interface is not disturbed by a large current flow, then a fixed fraction

of the photoelectrons should move from the selenium to iron under the influence of the field. For a given spectral distribution of the incident light, the linear relationship should extend down to zero illumination because, of course, the photo-electric threshold cannot depend on the rate at which photons strike the surface, but only on the energy per photon. We conclude that the data of Figure 2.2-2 can be used at least as an order-of-magnitude guide at the lowest illumination levels.

We may now summarize the process by which the energy of gamma radiation is to be converted into a meter indication in the phosphor-photovoltaic cell-meter circuit, by tracing the energy through the system. For the materials ( $Z \leq 48$ ) and gamma-ray energies (average 0.7 mev (11) ) of interest here, the photoelectric effect and pair production may be neglected in comparison to the Compton effect, so that the absorption of gamma-ray energy is proportional to the mass of the absorber (11). Since one roentgen represents the absorption of  $5.24 \times 10^7$  mev per gram of air (12), we have as the rate of energy absorption by one gram of phosphor from one roentgen per hour:

$$5.24 \times 10^7 \frac{\text{mev}}{\text{hr.}} \times 1.6 \times 10^{-13} \frac{\text{joule}}{\text{mev}} \times \frac{1}{3600} \frac{\text{hr}}{\text{sec}} \\ = 2.3 \times 10^{-9} \text{ watts.}$$

the need at least as an anti-Communist side of the Soviet  
 per system. We consider that the kind of thing which  
 which persons who are workers, but only on the theory  
 the Communist line would stand against in the case of  
 should receive from the Soviet Union, at least,  
 relation of the industrial side, the Soviet relationship  
 would the relations of the Soviet Union to the Soviet side  
 of the Communist side would stand against in the case of  
 the Soviet Union. We consider that the kind of thing which

[illegible]

$\frac{70}{100} = \frac{x}{100}$   $\frac{70}{100} = \frac{100}{x}$   $x = 100$



The efficiency with which the phosphor converts this power into light, (paragraph 2.3), is 0.15 for Zn-CdS. The fraction of emitted light reaching a sensitive cell surface can approach unity if we use a thin phosphor disc between two cells of the same surface area and shape as the phosphor. However for this example we shall use a single cell for which, with a thin phosphor, this fraction might be about 0.4. The relative sensitivity of the photocells for the incident light spectrum was calculated in paragraph 2.3 above as 0.95 for Zn-CdS.

Thus far we have traced the energy to the point where it produces output current from the photocells, which we may now write as:

$$i = 2.3 \times 10^{-9} \frac{(\text{watts absorbed})}{(\text{r/hr}) - \text{gram}} \times 0.15 \frac{(\text{watts emitted})}{(\text{watts absorbed})}$$

$$\times 0.4 \times 0.95 \times I_0 \frac{(\text{amperes})}{\text{watt}} = 1.6 \times 10^{-10} I_0$$

amperes/r/hr/gram phosphor,

where  $I_0$  is the response of the photocells in amperes per watt incident.

An approximate evaluation of  $I_0$  can be made by reference to Figures 2.1-2 where it is seen that the limiting slope at low illumination for the larger external resistances (for which power output is greatest) is approximately 3.2 micro-

The following table shows the results of the  
experiments made with the apparatus described in  
the preceding section. It is seen that the  
rate of reaction is very low and that the  
reaction is very slow. The results are given  
in the following table. The rate of reaction  
is very low and the reaction is very slow.  
The results are given in the following table.

It is seen that the rate of reaction is very low  
and that the reaction is very slow. The results  
are given in the following table.

$$1 = 2.7 \times 10^{-9} \quad (1/2 \text{ mole})$$
$$2 = 0.4 \times 10^{-9} \quad (1/2 \text{ mole})$$

The results of the experiments are given in the  
following table. It is seen that the rate of  
reaction is very low and that the reaction is  
very slow. The results are given in the  
following table.

amperes/foot-candle. The cell represented by the curve has an area of  $(1.1/144) = 0.0076 \text{ ft.}^2$ , and 1 lumen of tungsten light at  $2700^\circ$  Kelvin is equivalent to about 0.0039 watts in the visible range, hence  $I_0$  becomes:

$$I_0 = \frac{3.2 \times 10^{-6}}{0.0039 \times 0.0076} = 0.11 \text{ amperes/ watt incident.}$$

Thus we arrive at an estimated photocell current of

$$i = 1.6 \times 10^{-10} \times 0.11 = 1.8 \times 10^{-11} \text{ amperes/r/hr/gram}$$

phosphor for the conditions stated. In view of the several approximations involved, this figure should be regarded only as an upper limit for the current. As such, we may calculate the minimum radiation measurable with the phosphor-cell-ammeter circuit. If 0.1 microampere is taken as the minimum current measurable with a readily portable moving-coil instrument, and assuming a phosphor of mass 10 grams, we could detect approximately:

$$\frac{10^{-7}}{1.8 \times 10^{-11} \times 10} = 550 \text{ roentgens per hour,}$$

an impractically large minimum for a portable instrument to be used for the monitoring of human exposure to radiation.



regarding the results of the tests. The only results of the tests are as shown in Table I. The results of the tests are as shown in Table I. The results of the tests are as shown in Table I.

$$I = 1.5 \times 10^{-10} \times 0.11 = 1.65 \times 10^{-11} \text{ amperes/cm}^2$$

These are the results of the tests. The results of the tests are as shown in Table I. The results of the tests are as shown in Table I. The results of the tests are as shown in Table I.

Proportion for the results shown. In view of the results of the tests, the results of the tests are as shown in Table I. The results of the tests are as shown in Table I. The results of the tests are as shown in Table I.

$$I = 1.5 \times 10^{-10} \times 0.11 = 1.65 \times 10^{-11} \text{ amperes/cm}^2$$

These are the results of the tests. The results of the tests are as shown in Table I. The results of the tests are as shown in Table I. The results of the tests are as shown in Table I.

## 2.5. Experiments and Conclusions.

Despite these discouragingly large estimates some exploratory experiments were made. These will be briefly described:

- (a) A large anthracene crystal of excellent quality, mass 175 grams, was placed on a General Electric IV-1 photovoltaic cell. Current output of the cell was read by a Leeds and Northrup galvanometer. The crystal was irradiated with a  $\text{Co}^{60}$  source (0.98 rhr) of gamma rays separated from the crystal only by two thicknesses of black cloth, such that the estimated gamma radiation on the crystal surface facing the cell was 400 roentgens per hour. A maximum current of  $9 \times 10^{-10}$  amperes was measured. (This result cannot be compared with the calculation of the preceding section because the emission spectrum of anthracene is widely different from that of the sulfide phosphors.)
- (b) A phosphor consisting of 9.7 grams of Zn-CdS (Cu) dispersed in a polystyrene binder formed into a disc 3 mm. thick and 5 cm. in diameter was placed between two General Electric IV-2 photovoltaic cells (see last paragraph, Section





2.2) connected in parallel, with output fed to a Beckman micro-microammeter. The phosphor was irradiated by the same  $\text{Co}^{60}$  source used above, such that the average radiation over the faces of the phosphor disc was greater than 500 roentgens per hour. Average current reading was  $2 \times 10^{-10}$  amperes, or

$$\frac{2 \times 10^{-10}}{10 \times 500} = 4 \times 10^{-14} \text{ amperes/r/hr/gram}$$

phosphor, so that the estimate of maximum current in Section 2.4 is too high by a factor of greater than  $10^3$ .

We conclude that the simple phosphor-photovoltaic cell-ammeter circuit cannot at present form the basis for a practical radiation meter requiring no source of energy other than the energy of the gamma radiation measured. Several schemes have come to mind or have been suggested by others for improving the sensitivity of the device. One example is the n-layer sandwich, each layer consisting of cell-phosphor-cell. If these were connected in series, then in principle, at least, the open-circuit voltage under small irradiation could be made as large as we pleased by making n very large. Or consider two concentric spheres, one much larger than the other. The interior of the larger sphere

14. The following is a summary of the results of the experiments conducted in the laboratory of the U.S. Navy, Bureau of Naval Weapons, Division of Naval Ordnance, in the summer of 1945. The experiments were conducted in the laboratory of the U.S. Navy, Bureau of Naval Weapons, Division of Naval Ordnance, in the summer of 1945. The experiments were conducted in the laboratory of the U.S. Navy, Bureau of Naval Weapons, Division of Naval Ordnance, in the summer of 1945.

would be coated with a good phosphor, and the exterior of the inner sphere would be divided into many small segments, each forming a separate photo-voltaic cell, again with all segments connected in series. If these or other similar schemes seem attractive, they lose much of their promise when we consider that a sensitivity improvement of at least  $10^4$  is required, and for this we probably would do better with one new high-sensitivity detector, than with a large number of photo-voltaic cells.

At this point in the work we shifted to the human eye as the detector, and no further experiments with photo-voltaic cells were undertaken.



should be coated with a good phosphor, and the exterior of the inner sphere would be divided into many small segments, each forming a separate photo-voltaic cell, again with all segments connected in series. If these or other similar schemes seem attractive, they lose much of their promise when we consider that a sensitivity improvement of at least  $10^4$  is required, and for this we probably would do better with one new high-sensitivity detector, than with a large number of photo-voltaic cells.

At this point in the work we shifted to the human eye as the detector, and no further experiments with photo-voltaic cells were undertaken.

## CHAPTER 3

### PHOTONIC VIEWED BY THE EYE

#### 3.1. Characteristics of the Eye.

The extraordinary sensitivity of the human eye can be appreciated by considering the energy flow in the form of luminous flux which can just be perceived by a completely dark-adapted eye. Varying estimates have been given of this quantity (21), a conservative statement being (21) that it is less than  $10^{-16}$  watts, or, expressed in photons of light at the wavelength of maximum sensitivity of the eye, less than 300 elementary photons per second.

In order to take advantage of this sensitivity for visual detection and measurement of radiation, we must examine some other characteristics of the eye's response to light which will be discussed briefly as follows:

- (a) Relative visibility and Purkinje effect.
- (b) Contrast sensitivity variation.
- (c) Change in light threshold during adaptation.
- (d) Light and color thresholds.

(a) The familiar relative visibility curve for the light-adapted eye, in the form agreed upon by international convention (22), appears as curve (a) in Figure 3.1-1. The sensitivity of the eye is relatively constant at ordinary





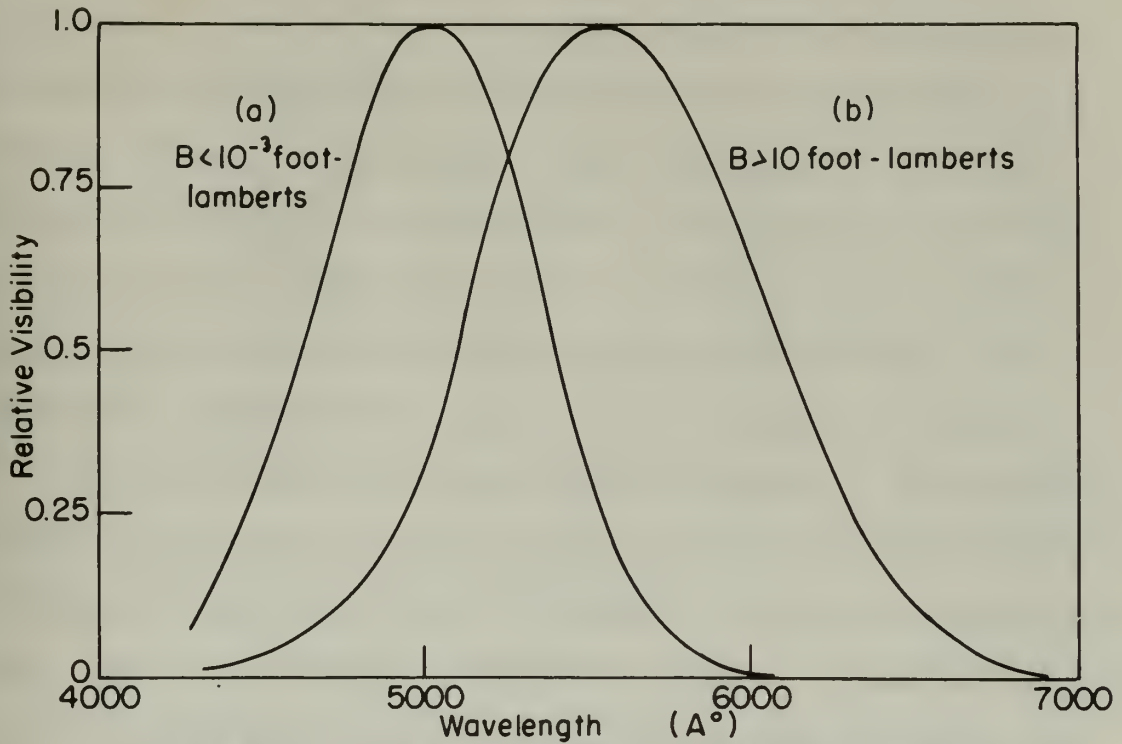


Figure 3.1-1 RELATIVE VISIBILITY CURVES (Walsh, W2)

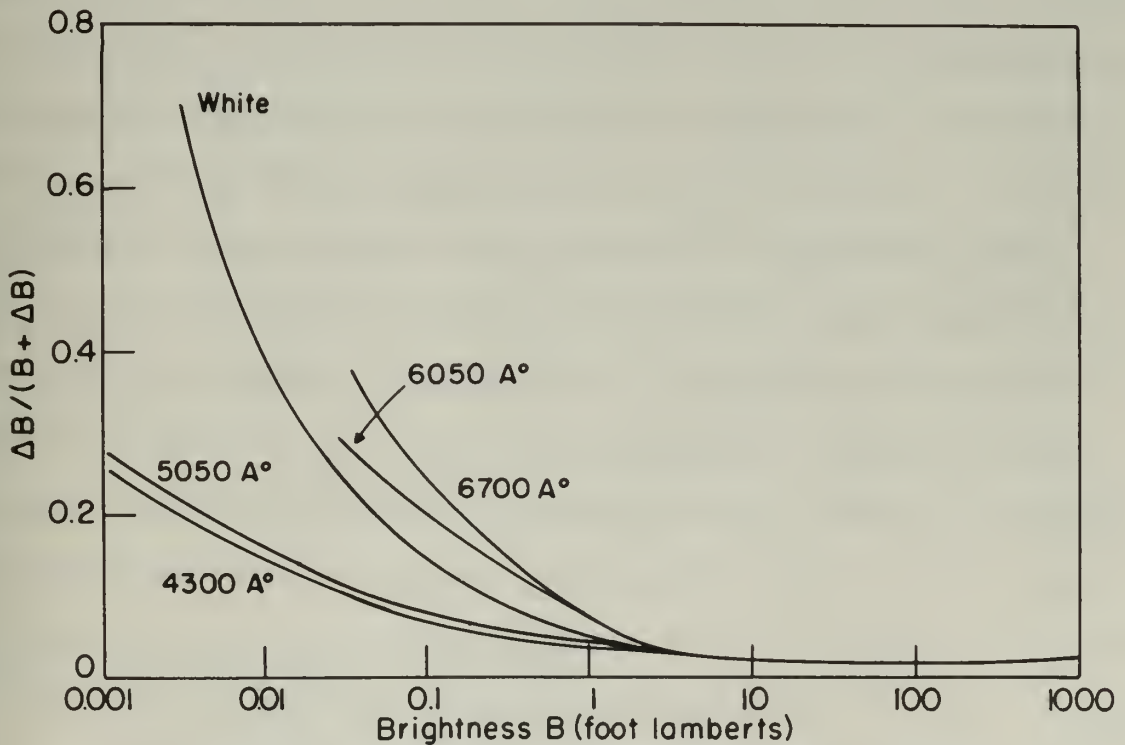


Figure 3.1-2 VARIATION OF PERCEPTIBLE CONTRAST WITH BRIGHTNESS (I.C.T., 11)



light levels, but as the adaptation brightness decreases, the visibility curve begins, at about 10 foot-lamberts, to shift to shorter wavelengths. This phenomenon, known as the Purkinje effect, is accompanied by a decrease in width of the curve, as indicated by (b) in Figure 3.1-1, which represents the visibility from brightnesses of less than about  $10^{-3}$  foot-lamberts down to the threshold of vision.

(b) The fractional brightness difference, or contrast,  $\Delta B / (B + \Delta B)$ , between two surfaces, which can just be perceived, is shown in Figure 3.1-2 as a function of field brightness and color (W2). It is noted that at the higher levels of illumination, the perceptible brightness difference is small and nearly constant for all colors, but increases as field brightness decreases, and that the Purkinje effect is manifested in an earlier widening of the perceptible brightness difference for the red end of the spectrum than for the blue. Two further facts which are not indicated in the figure are that the ability to distinguish brightness difference, especially at low light levels, is improved by a reduction in angular field of view (W2) and that the perceptible contrasts indicated in Figure 3.1-2 can be reduced, at any color or brightness, by a practiced observer judging the mean of the points of first appearance of inequality in each direction. Walsh (W2) states that the average of many readings taken in this way has been found to improve contrast perception by a factor



light levels, but as the adaptation brightness decreases, the visibility curve begins, at about 10 foot-lamberts, to shift to shorter wavelengths. This phenomenon, known as the Purkinje effect, is accompanied by a decrease in width of the curve, as indicated by (d) in Figure 3.1-1, which represents the visibility from brightnesses of less than about  $10^{-3}$  foot-lamberts down to the threshold of vision.

(d) The fractional brightness difference, or contrast,  $\Delta B/B$ , between two surfaces, which can just be perceived, is shown in Figure 3.1-2 as a function of field brightness and color (W3). It is noted that at the higher levels of illumination, the perceptible brightness difference is small and nearly constant for all colors, but increases as field brightness decreases, and that the Purkinje effect is manifested in an earlier widening of the perceptible brightness difference for the red end of the spectrum than for the blue. Two further facts which are not indicated in the figure are that the ability to distinguish brightness difference, especially at low light levels, is improved by a reduction in angular field of view (W3) and that the perceptible contrast indicated in Figure 3.1-2 can be reduced, at any color or brightness, by a practiced observer judging the mean of the points of first appearance of inequality in each direction. Walsh (W3) states that the average of many readings taken in this way has been found to improve contrast perception by a factor

of 8, under favorable conditions.

(c) The gradual improvement in sensitivity of the eye after illumination has been greatly reduced is illustrated by Figure 3.1-3, from (S1). (The ordinate of this curve is the logarithm of the reciprocal of the threshold brightness at the time indicated.) It is interesting to note that, although dark adaptation is essentially complete after 40 minutes, some increase in sensitivity has been reported after as long as 16 hours of adaptation (S1).

(d) Figure 3.1-4 presents the color and light thresholds (S2) plotted as functions of wavelength. In the red, recognition of color and the perception of light both vanish at very nearly the same retinal illumination, but as wavelength decreases, it is possible to perceive light at illumination levels much lower than those required for color recognition, in the region of the so-called twilight vision. (The unit of brightness used in this curve is the photon, equal to the illumination of the retina of the eye, when the pupillary aperture is one square millimeter, by an object having a brightness of one candle per square meter, or 0.292 foot-lamberts.)

### 3.2. The Visual Radiation Meter.

#### (a) Principle of operation.

In 1911, Lord Rutherford (M5) utilized the lumi-







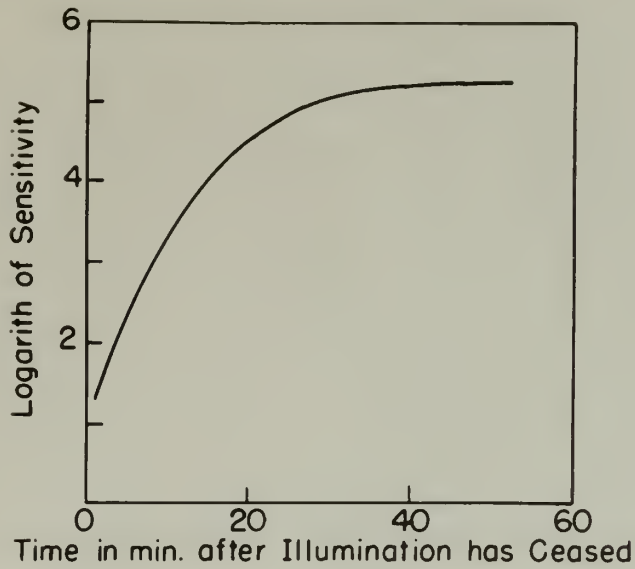


Figure 3.1-3 RISE OF SENSITIVITY OF THE RETINA WITH CONTINUED DARK-ADAPTATION OF THE EYE. (Southall, SI)

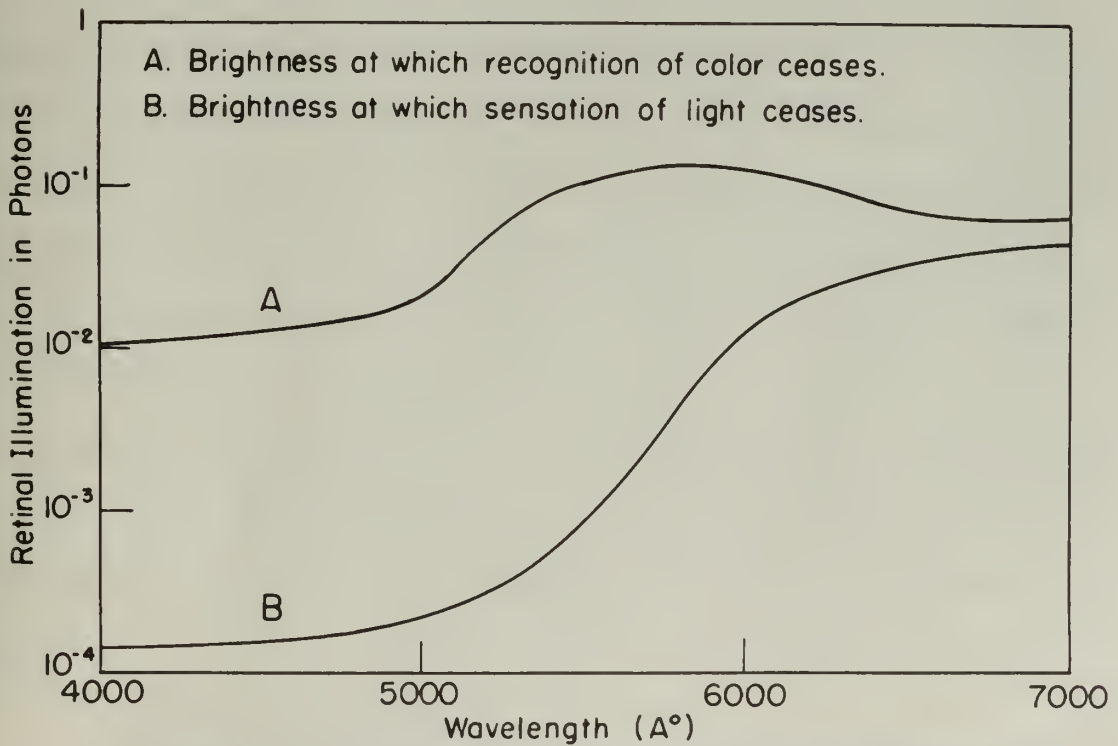


Figure 3.1-4 EXTINCTION OF LIGHT AND COLOR (Walsh, W2)



nescence of a zinc sulfide screen for visual detection of nuclear radiation in his classic experiments on alpha-ray scattering. The device proposed and developed in the present work rests on the same principle used by Rutherford, but we are primarily interested in the detection and quantitative measurement of gamma radiation, rather than counting individual alpha particles. To accomplish this, we introduce a standard light source of variable brightness, with which the zinc sulfide (or other phosphor) screen, excited to luminescence by the gamma radiation to be measured, is compared. The act of adjusting the intensity of the standard light source to obtain a brightness match then serves to measure the gamma radiation. The lever, dial, or other means by which the standard source is adjusted can be calibrated directly in roentgens per hour. It is important to note that we have here a dosage rate meter, not an integrating dosimeter, and that, if practical, it would certainly constitute one of the simplest rate meters for gamma radiation yet devised. We proceed therefore to examine the design criteria and practicality of such a device, to consider some of the possible variations, and to demonstrate the characteristics and performance of one form of the complete instrument.

(b) Choice of Phosphor.

Turning first to the luminescent material, or



necessity of a time knife versus the visual definition of  
mutual radiation in his classic experiments on light-ray  
splitting. The device proposed and described in the pre-  
sent work rests on the same principle used by Michelson,  
but we are primarily interested in the definition and possible  
relative measurement of gamma radiation, rather than measuring  
individual light particles. To accomplish this, we intro-  
duce a standard light source of variable brightness, with  
which the time knife (or other program) is used, assisted  
in luminance by the gamma radiation to be measured, is  
operated. The way of adjusting the intensity of the stan-  
dard light source to obtain a brightness equal to the  
to measure the gamma radiation. The latter, also, or other  
means by which the standard source is adjusted can be sub-  
stituted directly in research per hour. It is important to  
note that we have here a double test meter, not an inter-  
ring detector, and that, if possible, it would certainly  
constitute one of the simplest tests known for gamma radia-  
tion per device. We proceed therefore to examine the de-  
sign criteria and possibility of such a device, to consider  
some of the possible variations, and to summarize the obser-  
vations and performance of one form of the complete in-  
strument.

# (1) Design of Instrument

Turning first to the luminance meter, or

phosphor, it is apparent that maximum sensitivity will be attained if we choose a phosphor with a high efficiency for the conversion of gamma radiation into light, with as much as possible of the emitted light falling in the wavelength band where the eye has maximum sensitivity. But for the Purkinje effect, choice of a phosphor for visual observation could be considered as a problem identical with choosing a phosphor to be viewed by a photo-voltaic cell (Section 2.3). However, we now wish to find an efficient energy converter whose spectral emission maximum falls at the same wavelength as the peak sensitivity of the eye, at the brightness levels expected from the radiation to be measured.

We calculate the order of magnitude of the surface brightness of a thin phosphor disc 1 1/2 inches in diameter, containing 10 grams of phosphor of efficiency 0.2, excited by, say, 0.1 roentgens per hour. Using the calculation of Section 2.4, that the power absorbed by 1 gram of phosphor from 1 roentgen per hour is approximately  $2.3 \times 10^{-9}$  watts, we find this brightness to be:

$$2.3 \times 10^{-9} \frac{\text{watts}}{\text{gram} \cdot \text{r/hr}} \times 10 \text{ grams} \times 0.1 \text{ r/hr} \times 0.2$$

$$\frac{\text{watts emitted}}{\text{watts absorbed}} \times \frac{621 \text{ lumens/watt}}{\frac{1.75}{144} \text{ ft.}^2} \times \frac{1}{2}$$

However, it is necessary that certain sensitivity will be obtained in the system. It is necessary that a high efficiency for the conversion of power radiation into light, with an equal as possible of the emitted light being in the wavelength band where the eye has maximum sensitivity. All the power available should be used in a manner for visual observation. It should be considered as a problem to design a system which is viewed by a photo-voltaic cell (Section 5.3).

However, we are able to find an elliptical shape convenient for optical radiation emission. This is the case for the as the point sensitivity of the eye at the wavelength levels expected from the radiation to be measured.

In calculating the order of magnitude of the system, the maximum of a light source does  $1 \frac{1}{2}$  inches in diameter. Concentration is given at a point of intensity 0.5, which is 0.5 m. 0.1 centimeter per inch. Using the relationship of Section 5.4, that the power density is 1 watt per square foot, 1.57 watt per inch is approximately  $0.5 \times 10^{-7}$  watt. We find this relationship to be

$$0.5 \times 10^{-7} \text{ watt} \times \frac{1 \text{ inch}^2}{6.45 \times 10^{-2} \text{ m}^2} = 7.75 \times 10^{-9} \text{ watt/m}^2$$

$$\frac{0.5 \text{ watt}}{6.45 \times 10^{-2} \text{ m}^2} = 7.75 \times 10^{-9} \text{ watt/m}^2$$

$$\frac{0.5 \text{ watt}}{6.45 \times 10^{-2} \text{ m}^2} = 7.75 \times 10^{-9} \text{ watt/m}^2$$



or:

$$B = 1.2 \times 10^{-5} \text{ lumens/rt}^2.$$

In this calculation we have neglected emission from the edge of the disc, total internal reflection, and absorption of the emitted light by interior phosphor crystals, and have assumed that all the light is emitted at the wavelength of maximum sensitivity of the eye. If the emitting surface is perfectly diffuse, we may express this brightness as the same number of foot-lamberts. We note from curve (b) of Figure 3.1-1 that at this brightness the wavelength of maximum sensitivity of the eye is about 5040 Angstrom units, so that we seek a phosphor whose emission peak is at this same wavelength. Furthermore, for best results, the emitted light should have a spectral distribution no broader than the visibility curve at this brightness.

Selection of a commercially available phosphor on the basis of a specified shape and placement of its emission curve is not readily accomplished particularly when only a small amount is desired. The characteristics of a particular shipment of luminescent material are not necessarily identical to those of the preceding shipment, and the manufacturers are not ordinarily willing to guarantee their product in this respect. After inspection of several compilations of phosphor characteristics, those published by Leverenz (12-15) being

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$$S = 1.2 \times 10^{-2} \text{ lumens/m}^2$$

In this calculation we have neglected distance from the eye of the observer, total internal reflection, and absorption of the emitted light by interocular tissues, and have assumed that all the light is emitted at the wavelength of maximum sensitivity of the eye. It is well known that in practice, of course, we may assume this brightness as the total number of foot-lamberts. We note from curve (b) of Fig. 1-1 that at this wavelength the wavelength of maximum sensitivity of the eye is about 5000 Angstrom units, so that we need a frequency whose radiant power is at this same wavelength. Furthermore, for good results, the emitted light should have a spectral distribution as broad as the visible range of this brightness.

Calculation of a commercially available power on the basis of a specified area and diameter of the emitting surface is not readily accomplished particularly when only a small amount is desired. The manufacturer of a particular amount of luminous material and the manufacturer to whom of the preceding shipment, and the manufacturer are not generally willing to guarantee their product as this respect. After inspection of several quantities of various characterizations, those published by Lawrence (1945) being

most valuable, two phosphors were obtained whose spectral emission bands were in the desired region:  $\text{Zn-CdS}(\text{Cu})^1$ , and  $\text{Zn}_2\text{SiO}_4(\text{Mn})^2$ , the former being, according to Kallman (21), more than twice as efficient as the latter, and this was borne out by the results obtained here. For use in the visual radiation meter these phosphors, obtained in the form of powder, were mixed with a plastic binder, molded into discs of convenient size, and tested for efficiency, as described in detail in Chapter 4. Tests under gamma-ray excitation, described in Section 3.3, show that for  $\text{Zn-CdS}(\text{Cu})$ , the brightness calculation above is of the correct order of magnitude.

Spectral distribution curves for each of these phosphor materials, formed into discs with lucite, were obtained from an automatic-recording, grating spectrograph under unfiltered ultra-violet excitation. These results are shown in Figures 3.2-1 and 3.2-2. The emission curve for  $\text{Zn-CdS}(\text{Cu})$  follows very closely the shape of the threshold visibility curve, but peaks at a wavelength of 5875 Angstrom units, somewhat higher than was desired. Nevertheless, the overlap between the  $\text{Zn-CdS}$  curve and the threshold curve in-

- 
1. Type B phosphor, Patterson Screen Division, E. I. duPont de Nemours Co. Towanda, Pa.
  2. Type 33-1-25 phosphor, Tube Parts Department, Radio Corporation of America, Harrison, N.J.





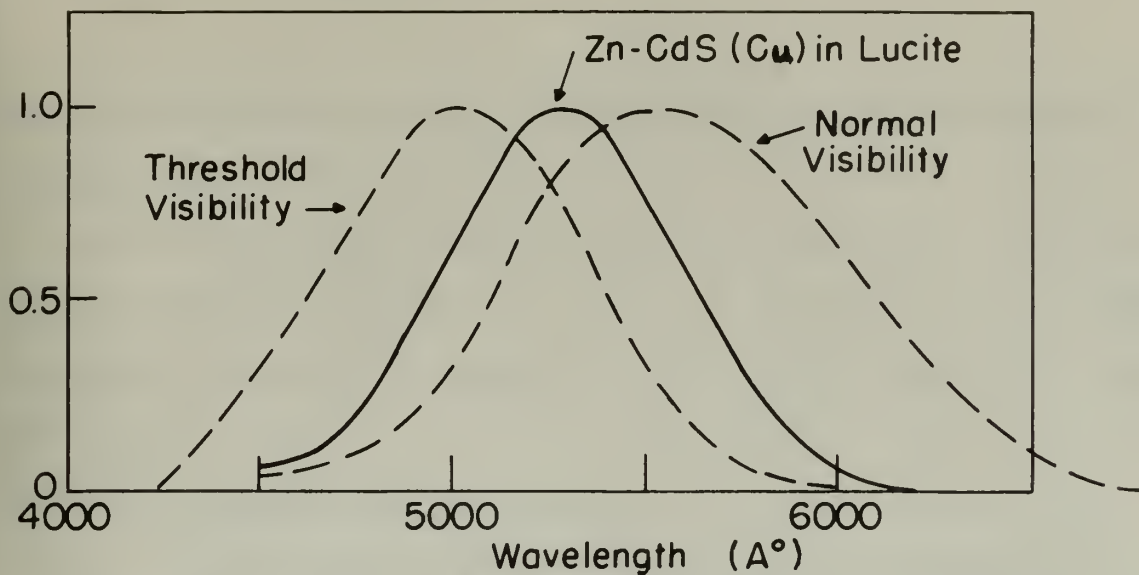


Figure 3.2-1 SPECTRAL DISTRIBUTION OF EMISSION FROM Zn-CdS (Cu) IN LUCITE COMPARED WITH NORMAL AND THRESHOLD VISIBILITY CURVES.

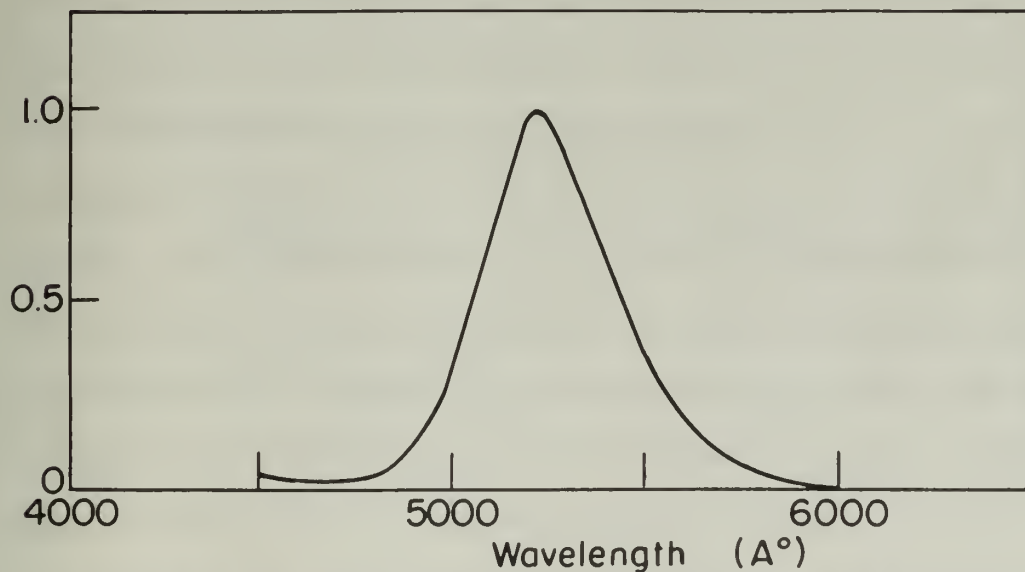
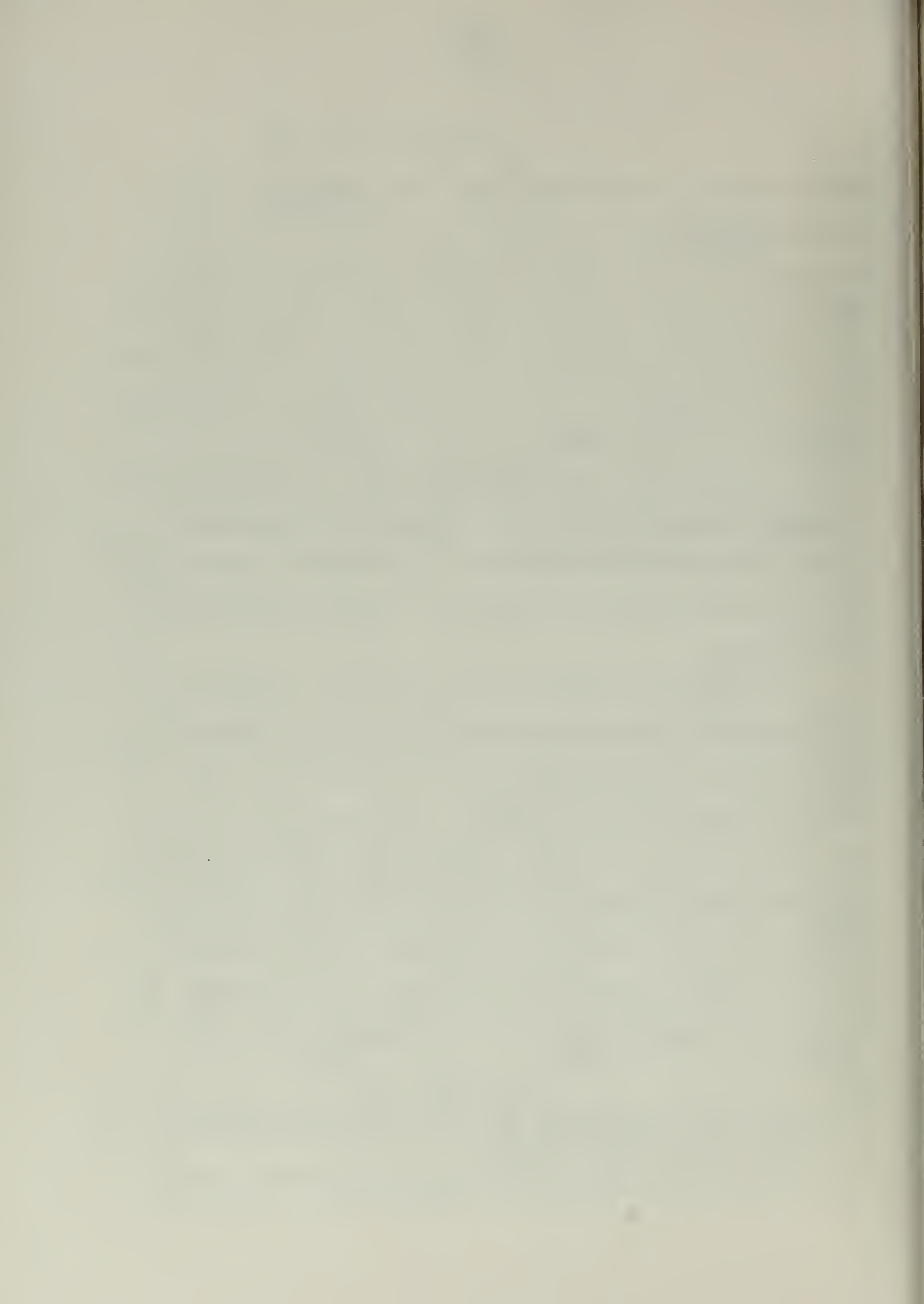


Figure 3.2-2 SPECTRAL DISTRIBUTION OF EMISSION FROM Zn<sub>2</sub>SiO<sub>4</sub> (Mn) IN LUCITE





icates that this phosphor would be fairly satisfactory for our purpose.

The  $\text{Zn}_2\text{SiO}_4$  (44n) emission spectrum peaks at a slightly shorter wavelength ( $5210 \text{ \AA}^0$ ), and has essentially the desired shape, but, as will be seen, its total light emission is much inferior.

(c) Standard Light Source.

In order to avoid uncertainties introduced by the Purkinje effect into the task of matching the brightness of two surfaces of different color, we require that the standard light be identical in spectral distribution with that of the detector phosphor. The standard source, of course, could consist of a battery-powered light bulb, suitably filtered, but this arrangement is objectionable in the present application because of battery shelf-life (and active life), and because color temperature complications arise if the intensity of the emitted light is varied by adjusting filament current. The latter can be avoided by other methods of varying intensity but the batteries remain. We therefore consider the possibility of using a phosphor excited by a source of radioactivity, built into the instrument, as the comparison light source.

The source of excitation energy for such a phosphor should have a half-value period of several years, and if, for

disorder that this phosphor would be fairly satisfactory for  
our purpose.

The  $\text{Ba}_2\text{SO}_4$  (m) emitting spectrum from a slightly  
shorter wavelength (2510 Å), and has essentially the desired  
shape, but, as will be seen, the total light emission is much  
inferior.

# (c) Standard Light Source.

In order to avoid uncertainties introduced by  
the varying effect into the task of emitting the brightness  
of two surfaces of different color, we require that the sur-  
face light be identical in spectral distribution with that  
of the standard phosphor. The standard source, of course,  
could consist of a battery-powered light bulb, suitably fil-  
tered, but this arrangement is objectionable in the present  
application because of battery wear-life (and active life),  
and because color temperature considerations arise in the in-  
terplay of the emitted light is varied by changing filament  
current. The latter can be avoided by other means of very-  
low intensity but the battery remains. It therefore considered  
the possibility of using a phosphor excited by a source of  
radioactivity, built into the instrument, as the comparison  
light source.

The source of excitation energy for such a phosphor  
should have a half-value period of several years, and it, for



comparison purposes, the standard light source is to be mounted close to the detector phosphor, the former should not emit penetrating radiation which would cause luminescence of the latter. Thus we eliminate from consideration the radium and thorium series, because of their gamma components, and polonium (low gamma emission) because of its short life (139 days). In fact, the standard tabulations of the radio-active nuclides (33), and (34), reveal no alpha emitters which meet our specifications. Several beta-ray sources emitting no gamma rays are available in quantity from the Isotopes Division of the Atomic Energy Commission (A1) or from distributors. Of these, strontium-90 is among the least expensive and the available energy per disintegration from this nuclide is comparatively large.  $\text{Sr}^{90}$ , a fission-product daughter of two very short-lived beta-ray emitters, decays (P1) according to the scheme:



Hence, when secular equilibrium has been attained, each decay of a  $\text{Sr}^{90}$  nucleus yields two beta particles, with an average energy release of about 0.9 Mev per disintegration.

The extensive literature on phosphors includes very few precise data on the brightness obtainable from self-excited phosphors, and none at all has been located on the





possible deterioration of luminescence in such a phosphor as a result of constant bombardment of the phosphor crystal structure by beta-rays. That this last point may be of importance in the present problem is illustrated by the decay with time of the luminescence from the self-luminous paints on watch and instrument dials, signs, etc., most of which are excited by radiation from radium or mesothorium. The destructive effect of the radioactivity on the phosphor can, at least, be listed as a variable influencing the light output from a radio-active light source, the effect of which may be comparable with the effect of the half-life of the radio-active exciter.

The brightness of a copper-activated, green-emitting zinc sulfide screen (of unspecified thickness but presumably comparable to the range of radium alpha particles in ZnS, about  $5 \text{ mg/cm}^2$ ) under alpha-ray excitation has been measured by Blau and Feuer (B2). They coated a plate with 1 microgram of radium per square centimeter and placed it 4 millimeters from a phosphor screen in an evacuated chamber, obtaining a screen brightness of 1 to 2 micro-lamberts (0.001 to 0.002 foot-lamberts approximately) for use as a standard light source. Boardman and Dawson (B4) report brightnesses of up to 22.5 micro-lamberts from an intimate mixture of zinc sulfide with an alpha-emitting radio-active salt (otherwise unidentified).



possible destruction of luminance in such a manner  
as a result of constant bombardment of the phosphor screen  
structure by cathode rays. That this point may be of im-  
portance in the present context is illustrated by the fact  
with view of the luminance from the self-luminous points  
on wires and independent diode, triode, etc., must of which  
are excited by radiation from within or near-surface. The  
destructive effect of the radioactivity on the phosphor can,  
as stated, be taken as a reliable indication of the light out-  
put from a radio-active light source, the effect of which  
may be compared with the effect of the self-life of the  
radio-active emitter.

The brightness of a copper-coated, green-emitting  
line cathode screen (of unspecified diameter but presumably  
comparable to the range of radius light provided in the  
above  $\frac{1}{2}$  cm) under slightly excitation has been measured  
by Shaw and Yess (1931). They coated a glass with a layer  
of radius per square centimeter and found it to emit  
light from a phosphor screen as an evacuated chamber, ob-  
taining a green brightness of 1 to 2 micro-lamberts (0.001  
to 0.002 foot-lamberts approximately) for use as a standard  
light source. Borsman and Lawson (1931) report brightness  
of up to 25.2 micro-lamberts from an inside source of  
also similar with an alpha-emitting radio-active salt (other  
than unclassified).



Since both of these results were based on alpha excitation of the phosphor, whereas the present application requires gamma-free beta ray excitation, it became necessary to demonstrate that a usable brightness could be attained with a beta source.

$\text{Sr}^{90}$  in chloride solution, as obtained from the Atomic Energy Commission,<sup>3</sup> was precipitated as a carbonate by the addition of excess ammonium carbonate. The precipitate was permitted to stand for 24 hours, then filtered. The filter paper, carrying the  $\text{Sr}^{90}\text{CO}_3$  precipitate was cemented onto an aluminum disc 1 inch in diameter, and the active deposit, well distributed over an area  $3/4$  inches in diameter, was protected by a thin ( $1.5 \text{ mg/cm}^2$ ) aluminum foil. This disc was then mounted on a rod screwed into the back face of the disc for convenience in handling. The source so obtained had an activity, as measured by an ionization chamber comparison against a source of known activity, of  $0.5 (\pm 0.1)$  millicuries.

A phosphor made of 1.00 gram of Patterson Type B zinc-cadmium sulfide (copper activated) and molded by means of 0.50 grams of a lucite binder into a disc  $1 \frac{7}{16}$  inches in diameter and 0.05 inches thick, was placed on the source

---

3. Unusual care must be taken in work with  $\text{Sr}^{90}$ , for its long half-life, the energetic beta-ray from its daughter yttrium, and the fact that it appears to be a bone-seeker make it unusually toxic among beta emitters. The latest (January 1, 1951) recommendation of the International Commission on Radiological Protection (IC) is that the maximum permissible amount of strontium-90 in the body is 1.0 microcurie.





disc and the brightness of the phosphor measured with the Taylor Low-Brightness Meter, with the result, from a series of 7 measurements, of  $1.74 (\pm 0.05) \times 10^{-3}$  foot-lamberts. To reduce this brightness to familiar terms, it was noted that the phosphor's glow was detectable immediately when placed in the shadow under a desk or chair in a brightly lighted room.

From the brightness calculation above, for the gamma-irradiated detector phosphor, this brightness would be equivalent to gamma radiation producing approximately:

$$\frac{1.7 \times 10^{-3}}{1.2 \times 10^{-5}} \times 0.1 = 14 \text{ roentgens per hour}$$

which would thus be the upper detection limit for a meter using this particular beta source and comparison phosphor.

To increase the brightness of the standard or comparison phosphor, we may increase the source strength or make more efficient use of a given source activity. There appears to be no reason why the beta-source could not be mixed directly with the phosphor material and molded into a thin disc with plastic. Alternatively, activation of the completed phosphor-plastic disc by neutron bombardment in a reactor might be feasible, provided a suitable nucleus (such as beryllium) were included in the plastic or phosphor. If the active material were obtained with high specific activity,



placed in the shadow under a desk in a vicinity  
that the photograph was developed immediately when  
To know this photograph is familiar to him, it was noted  
at 7 o'clock, at 1.45 (1.45) x 10.5 feet-lambda.  
Taylor low-lightness taken, with the result, from a series  
also and the thickness of the photograph measured with the

From the Chinese information about the summer-  
winter festival, it is possible that the festival  
is a Chinese festival, and the Chinese people  
are very interested in it.

$$= 0.1 = 10\% \text{ of } 1.0 = 1.0 \times 10^{-1}$$

Two positive reactions were obtained with both specific reactivity. The bacillus was isolated in the plastic or porous. It might be possible, provided a suitable medium (such as phosphate-plastic) also by neutron bombardment in a reactor with plastic. Alternatively, activation of the irradiated with the phosphate material was added into a thin slice. It is no reason why the beam-source could not be used directly. In any instance, we may improve the source capacity by using

its presence in the phosphor-plastic mixture should not interfere significantly with the surface brightness of a thin phosphor. Of course such a procedure has the disadvantage that phosphor bombardment by the nuclear emission particles, with consequent possible destructive effect, is continuous, whereas with the source and phosphor separated, an absorber could readily be inserted when the meter is not in use. The manufacture of self-excited phosphors was not undertaken during this work because of the undesirability of contaminating the only available high-pressure lucite mold.

(d) Description of the Complete Meter.

Figures 3.2-3 and 4 are sketches of two of the many possible forms of the visual radiation meter. The sketches are self-explanatory, and a few comments on components not elsewhere mentioned will suffice.

The adjustment for a brightness match between a detector phosphor and the standard light source can readily be made with crossed polarizers (Figure 3.2-3). One type that appears to be satisfactory<sup>4</sup> is obtainable in the form of thin sheets which are easily mounted. Two such sheets have a transmission with optical axes parallel of 21%, and effect a reduction by a factor of 200 when the axes are crossed. If three such sheets are used, the center one

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4. Type HN-32, Polaroid Corporation, Cambridge, Mass. The transmission data herein were furnished by the manufacturer.







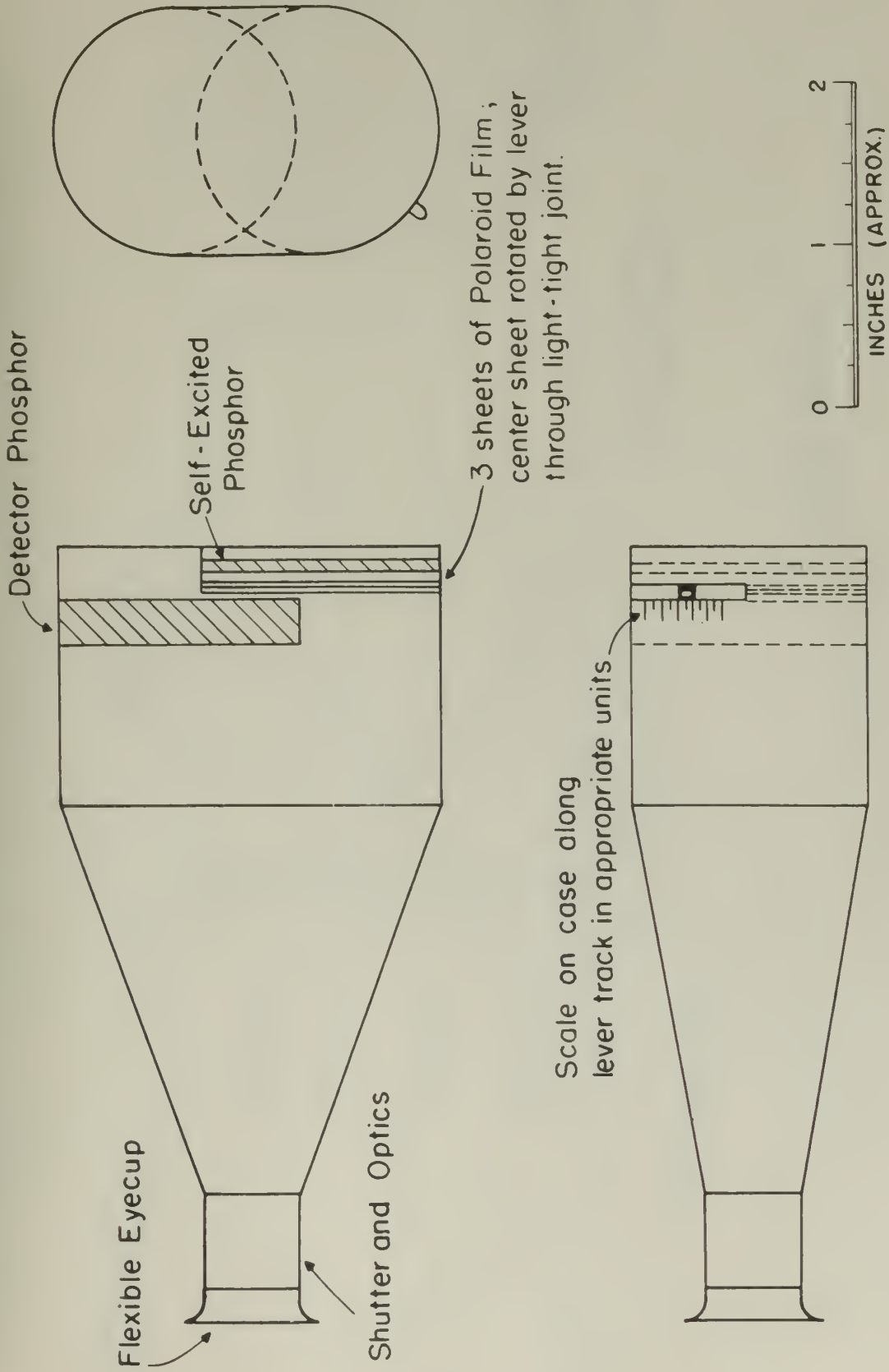


Figure 3.2-3 SELF-EXCITED PHOSPHOR MODEL OF THE VISUAL RADIATION METER



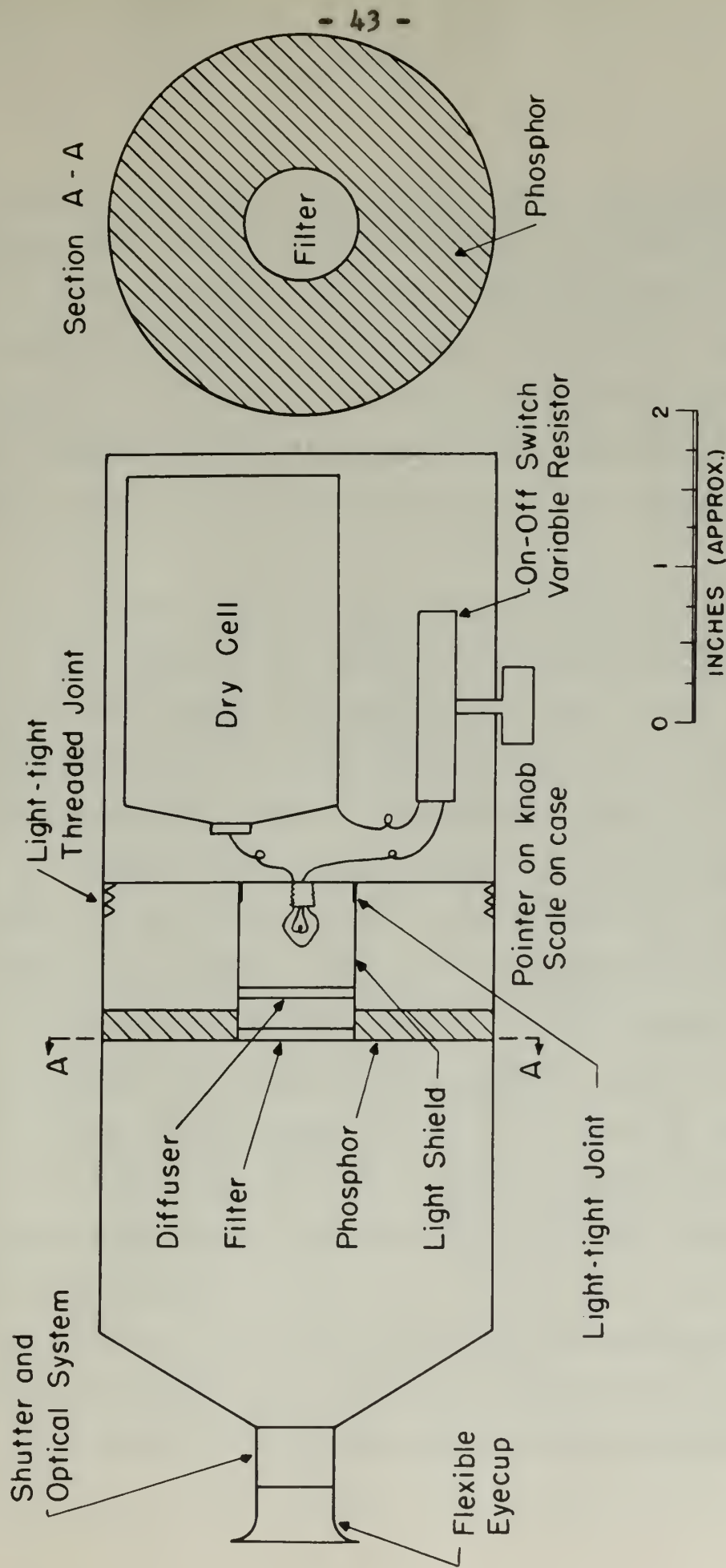
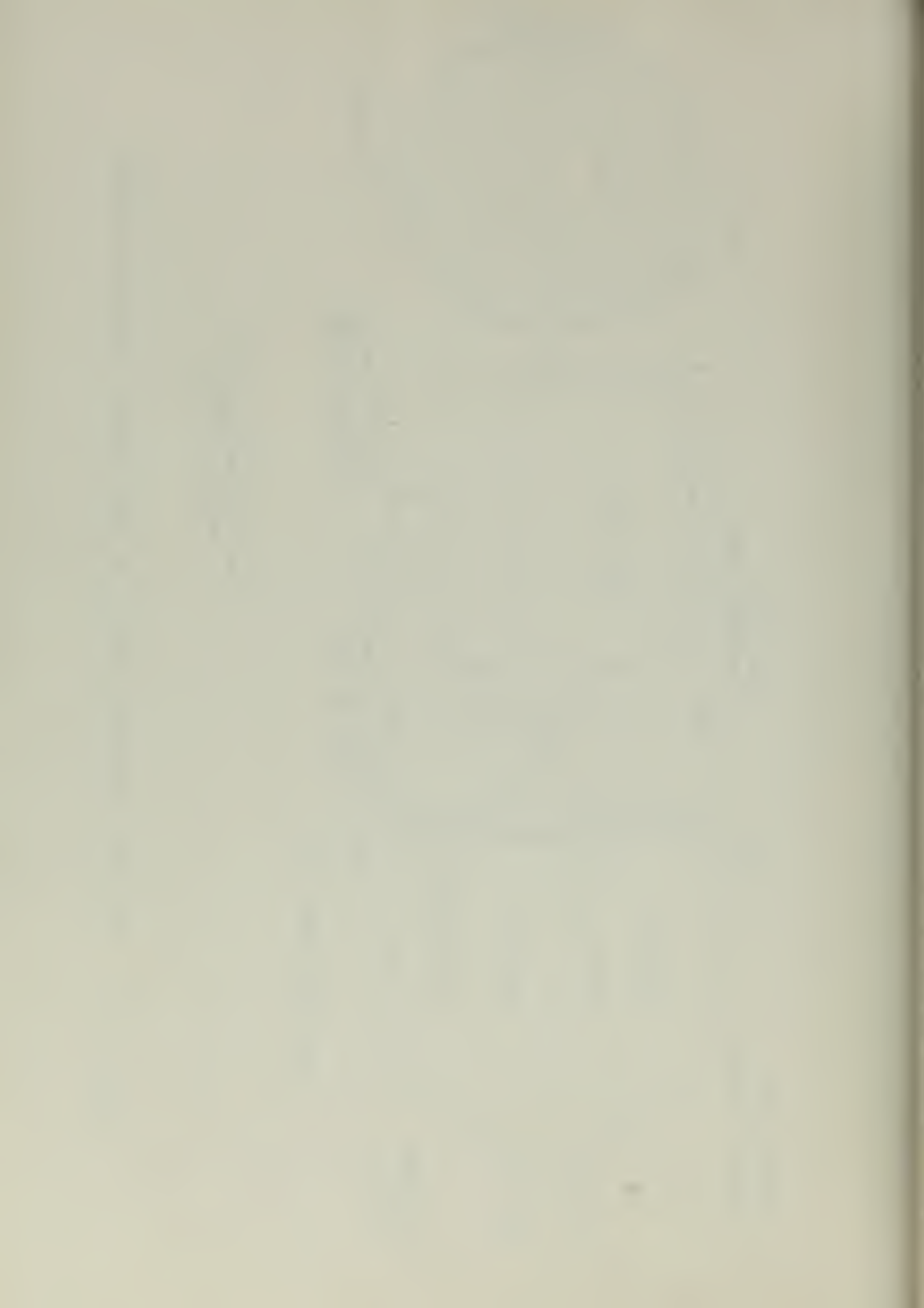


Figure 3.2-4 BATTERY-POWERED MODEL OF THE VISUAL RADIATION METER





being rotated while the other two are fixed, as shown in the figure, the open transmission is 13%, the maximum attenuation being a factor of 40,000. The transmission of this material is reduced, as the axes are rotated, quite uniformly in the region of the emission of zinc-cadmium sulfide (Figure 3.2-1), though there is a non-uniformity in the high and low wavelength regions of the visible spectrum.

The design of Figure 3.2-4 employs for simplicity a rheostat for adjusting the intensity of the standard lamp. As a result, the filter can correct the light to the spectral distribution of the phosphor emission over a narrow range of intensities, only. At very low brightness, in the domain of twilight (colorless) vision, this effect could be compensated by adjustment of the scale calibration, but at high intensities it would bring in the uncertainty of matching two surfaces of different colors. If this should be found to increase the overall error significantly, the intensity of the standard light should be adjusted by polaroids or an optical wedge, and an ammeter should be included in the circuit so that a fixed current could be maintained through the filament.

The optical system for viewing the two surfaces need be no more elaborate than a glass or plastic plate to exclude dust. In the case of the model using a beta-source to pro-

being rotated while the other two are fixed, as shown in the figure, the open transmission is 15%, the maximum transmission being a factor of 40,000. The transmission of this material is reduced, as the axes are rotated, quite uniformly in the region of the emission of line-radiation (figure 3.2-1), though there is a non-uniformity in the high and low wavelength regions of the visible spectrum.

The design of figure 3.2-4 employs for simplicity a rheostat for adjusting the intensity of the standard lamp. As a result, the filter can correct the light to the spectral distribution of the phosphor emission over a narrow range of intensities, only. At very low brightness, in the domain of twilight (colorless) vision, this effect could be compensated by adjustment of the scale calibration, but at high intensities it would bring in the uncertainty of matching two surfaces of different colors. If this should be found to increase the overall error significantly, the intensity of the standard light should be adjusted by means of an optical wedge, and an ammeter should be included in the circuit so that a fixed current could be maintained through the filament.

The optical system for viewing the two surfaces need be no more elaborate than a glass or plastic plate to exclude dust. In the case of the model using a cathode-ray tube



duce the standard light, the lens should be thick enough to shield the eye from the radiation. A shutter of some kind is necessary at the eyepiece because of the long phosphorescent decay of the sulfide phosphors after exposure to sunlight; a simple cap fitting over the eyepiece might be sufficient.

A number of variations on the general principle of visual observation of a phosphor for radiation measurement are possible. One of the simplest consists of a phosphor viewed through a series of openings of varying opacity in an opaque disc or strip. The openings could be in the form of numerals, a number code giving the approximate radiation dosage rate corresponding to the lowest number which could just be perceived. Such a device, with no standard for comparison, would, however, yield varying results depending on the degree of dark adaptation of the observer.

### 3.3. Tests of the Visual Radiation Meter.

#### (a) Brightness Standard.

The Taylor Low-Brightness meter (LEM) consists of a long (60 cm) open cylinder through which an observer views an illuminated circular area silhouetted against a circular field of the surface toward which the instrument is aimed, whose brightness is to be measured. The illuminated area, actually elliptical in shape, is a magnesium carbonate surface which reflects into the observer's eye

due the standard light, the lens should be thick enough to shield the eye from the radiation. A number of some kind is necessary at the expense of some of the lens properties. The body of the radiating phosphorus after exposure to sunlight; a simple cap fitting over the eyeless might be sufficient.

A number of variations on the general principle of visual observation of a phosphor for radiation measurement are possible. One of the simplest consists of a phosphor viewed through a series of openings at varying depths in an opaque disc or strip. The openings could be in the form of rectangles, a number code giving the approximate radiation of response corresponding to the lowest number which could thus be perceived. Such a device, with no standard for comparison, would, however, yield varying results depending on the degree of dark adaptation of the observer.

### 3.2. Tests of the Visual Radiation Meter

#### (a) Brightness Standards

The Taylor Ice-Brightness Meter (TBM) consists of a lens (50 cm) open cylinder through which an observer views an illuminated object even at distances against a circular field of the surface toward which the instrument is aimed, whose brightness is to be measured. The illuminated area, normally illuminated in shape, is a rectangular carbonate surface which reflects into the observer's eye



light emitted by a standard lamp through an aperture in the side of the main cylinder. The intensity of the standard light source is adjustable by filters and an optical wedge, so that by comparison of the circle, illuminated by the standard, with the external field of view, brightness can be measured over the range from  $10^{-1}$  to  $10^{-5}$  foot-lamberts. The standard lamp bulb operates at constant current, so that color changes do not accompany intensity, or brightness, changes of the reflecting surface. The instrument was calibrated by the manufacturer (General Electric Co.) just prior to its use in the present experiments, but no low-brightness standards were available for re-checking during the course of the work.

It is apparent, from this description of the LEM, that when it is used to measure the brightness of a phosphor luminescing under the excitation of gamma radiation, it becomes essentially a visual radiation meter similar to the form sketched in Figure 3.2-4. Use of the LEM in this way is subject to several limitations. The standard light source, a tungsten filament, has a color distribution far different from the essentially blue-green of the phosphor, so that at the higher radiation levels it is necessary to match green and pale yellow brightnesses. The most serious fault of this arrangement arises from the 60 centimeter length of the



light emitted by a standard lamp through an aperture in the side of the main cylinder. The intensity of the standard light source is adjustable by filters and an optical wedge, so that by comparison of the color, illuminated by the standard, with the external field of view, brightness can be measured over the range from  $10^{-1}$  to  $10^{-5}$  foot-lamberts. The standard lamp with aperture of constant diameter, so that color changes do not accompany intensity, or brightness, changes of the reflected surface. The instrument was calibrated by the manufacturer (General Electric Co.) just prior to its use in the present experiment, but no low-brightness standards were available for re-checking during the course of the work.

It is apparent, from this description of the L.M. that when it is used to measure the brightness of a phosphor luminescing under the excitation of gamma radiation, it becomes essentially a visual radiation meter similar to the form sketched in Figure 3-4. One of the L.M. in this way is subject to several limitations. The standard light source, a tungsten filament, has a color distribution for different from the essentially blue-green of the phosphor, so that at the higher radiation levels it is necessary to match green and pale yellow brightness. The most serious fault of this arrangement arises from the 60 centimeter length of the

LEM which forces placement of the phosphor so far from the eye that the field of view of the observer is not filled by the phosphor image, which subtends a cone of half-angle only  $2^{\circ}$ - $24'$  when a 2-inch phosphor is used, and of  $1^{\circ}$ - $49'$  with a 1 1/2-inch phosphor. Thus the threshold for detection of radiation with a given phosphor at the end of the LEM is much less than it would be for a smaller phosphor-to-eye distance.

(b) Detection Threshold, and Reproducibility of Measurements.

The minimum radiation which can be detected visually with the phosphors available, and the effect of distance between eye and phosphor were established by the following experiment. A phosphor disc 5 cm. in diameter was mounted at the end of a tube of the same inside diameter, 66 cm. long, with a black arrow-shaped figure 2 cm. long affixed to the face of the phosphor. Measurements were made of the maximum distance of a radium gamma source from the phosphor at which a dark-adapted observer could (a) determine without question the presence or absence of visible light from the phosphor, and (b) determine within  $30^{\circ}$  the angular orientation of the arrow. This procedure was then repeated with a tube 22 cm. long. The results, in terms of distance and roentgens per hour from the source (46.8 mgm. radium source, calibrated by the Bureau of Standards), calculated by the inverse square law, are given in Table 3.3-1.



The whole process placement of the phosphor on the tube end eye that the field of view of the observer is not filled by the phosphor image, which depends on a cone of half-angle only 2°-3°, when a 2-inch phosphor is used, and of 1°-1.5° with a

1 1/2-inch phosphor. Thus the threshold for detection of radiation with a given phosphor at the end of the tube is much less than it would be for a smaller phosphor-at-the distance.

(5) Detection Threshold, and Reproducibility of Measurements.

The minimum radiation which can be detected visually with the phosphors available, and the effect of distance between eye and phosphor were established by the following experiment. A phosphor disc 5 cm. in diameter was mounted at the end of a tube of the same inside diameter, 60 cm. long, with a black cross-shaped figure 2 cm. long etched on the face of the phosphor. Measurements were made of the maximum distance of a radium source from the phosphor at which a dark-adapted observer could (a) detect, also without question the presence or absence of visible light from the phosphor, and (b) determine within 30° the regular orientation of the arrow. This procedure was then repeated with a tube 52 cm. long. The results, in terms of distance and percentage per hour from the source (40.8 mCi. radium source, calibrated by the Bureau of Standards), collected by the observer against low, are given in Table 2-3-1.



TABLE 3.3-1

Detection Threshold, and Effect of Phosphor-to-Eye Distance.

(46.8 mgm radium source - 45.4 mrhm.)

Phosphor-to-eye distance (cm).	Observation	Maximum source-to-phosphor distance (cm), and minimum roentgens per hour.			
		Observer F		Observer K	
		Cm	r/hr	Cm	r/hr
66	Detection Threshold	70	0.093	70	0.093
66	Arrow Orien- tation	25	0.727	20	1.13
22	Detection threshold	180	0.014	165	0.017
22	Arrow Orien- tation	70	0.093	60	0.126

This experiment demonstrates that the minimum detectable gamma radiation with this phosphor material is less than 20 mr/hr under favorable conditions. Some rough experiments with phosphor-to-eye distances indicate that the optimum may be less than 22 cm, for a 5 cm diameter phosphor. Further investigation of this point might produce evidence for an even lower detection threshold than shown above.

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Revelation 19:11-13

(A. S. 1900 - 1901)

Distance (mi.)	Observed	Maximum distance (mi.)	Minimum distance (mi.)
25	0.000	0.000	0.000
50	0.000	0.000	0.000
75	0.000	0.000	0.000
100	0.000	0.000	0.000
125	0.000	0.000	0.000
150	0.000	0.000	0.000
175	0.000	0.000	0.000
200	0.000	0.000	0.000
225	0.000	0.000	0.000
250	0.000	0.000	0.000
275	0.000	0.000	0.000
300	0.000	0.000	0.000
325	0.000	0.000	0.000
350	0.000	0.000	0.000
375	0.000	0.000	0.000
400	0.000	0.000	0.000
425	0.000	0.000	0.000
450	0.000	0.000	0.000
475	0.000	0.000	0.000
500	0.000	0.000	0.000
525	0.000	0.000	0.000
550	0.000	0.000	0.000
575	0.000	0.000	0.000
600	0.000	0.000	0.000
625	0.000	0.000	0.000
650	0.000	0.000	0.000
675	0.000	0.000	0.000
700	0.000	0.000	0.000
725	0.000	0.000	0.000
750	0.000	0.000	0.000
775	0.000	0.000	0.000
800	0.000	0.000	0.000
825	0.000	0.000	0.000
850	0.000	0.000	0.000
875	0.000	0.000	0.000
900	0.000	0.000	0.000
925	0.000	0.000	0.000
950	0.000	0.000	0.000
975	0.000	0.000	0.000
1000	0.000	0.000	0.000

..Jensen, William, et al. 1984. *Adaptation and the Evolution of the*

100-443887-100

From 25 to 27 March 1968, the following observations were made:

Wanted with money-to-see witnesses regarding the 99-

STANDARD FORM NO. 64

THESE RESULTS ARE IN ACCORD WITH THE FINDINGS OF OTHER STUDIES.

For an even lower detection limit than shown above

It is evident from Table 3.3-1 that the three-fold reduction of the distance from which the phosphor was viewed brought about a six-fold improvement in threshold sensitivity, and an eight-fold decrease in the minimum radiation required for arrow orientation. In view of this result, measurements made with the Low-Brightness Meter used as a visual radiation meter can be regarded only as a gauge of the reproducibility of brightness readings at very low light levels. Since the LBM was the only available comparison device for the low light levels, and since no way could be found to use a shorter eye to phosphor distance without major alteration of the instrument, it was used for this purpose in the next experiment to be described.

Two observers with no prior knowledge of the Low-Brightness Meter and no significant experience in photometry were used in this experiment. Both had uncorrected visual acuity in both eyes of 20/20, or better, with normal color perception, and had sufficient knowledge of the use and effects of gamma radiation so that it can be assumed that no psychological effects on this account perturbed the measurements. The observers were dark-adapted for at least fifteen minutes in a red adaption brightness of less than  $10^{-2}$  foot-lamberts. The detector phosphor (Zn-CdS(Cu) in lucite) was 1 1/2 inches in diameter, viewed through the LBM so that it was 60 cm from the observer's eye. The phosphor



It is evident from Table 2-3 that the three-fold reduction of the distance from which the phosphor was viewed brought about a six-fold improvement in observer sensitivity, and an eight-fold decrease in the minimum reduction required for error orientation. In view of this result, measurements made with the low-brightness filter used as a visual reduction factor can be regarded only as a measure of the reproducibility of brightness readings at very low light intensities. Since this filter was the only available comparison device for the low light intensities, and since no way could be found to use a standard eye to measure distances without major distortion of the instrument, it was used for this purpose in the next experiment to be described.

Two observers with no prior knowledge of the low-brightness filter and no significant experience in photometry were used in this experiment. Both had corrected vision easily in both eyes of 20/30, or better, with normal color perception, and had sufficient knowledge of the eye and extent of human reaction so that it can be assumed that no psychological effects on this second part of the experiment. The observers were dark-adapted for at least fifteen minutes in a red adapted brightness of less than  $10^{-2}$  foot-lamberts. The observer (number 12-353104) is (female) was 1.75 inches in diameter, viewed through the lens so that it was 60 cm from the observer's eye. The phosphor

was irradiated by a 10 mgm (8.1 mrhm) radium source, from the distances (phosphor to source) shown in Table 3.3-2. Each observer was permitted about 10 minutes familiarization with the arrangement before the readings shown in the table were taken.

TABLE 3.3-2

Brightness Measurements by Inexperienced Observers

(10 mgm radium source, 8.1 mrhm. Brightness in  $10^{-6}$  foot-lamberts)

Distance phosphor to source:	9 cm.	10 cm.
Observer D	35	12.8
	31	19.6
	18	26.5
	<u>23</u>	<u>35</u>
Mean	26.7	23.5
Standard Deviation	9%	12%
Observer L	26	25
	31	31
	27.5	27
	<u>27.0</u>	<u>18</u>
Mean	27.9	25.2
Standard Deviation	5%	12%

was fitted with a 10 mm (0.1 mm) section source, from  
the distance (measured to source) shown in Table 1-2-2.  
Each observer was positioned about 10 minutes before the  
start of the experiment before the readings shown in the  
Table were taken.

TABLE 1-2-2

Distance measured by independent observers

(to gas section source, 0.1 mm, distance in 10<sup>-6</sup> foot-inches)

Distance measured by source:		10 mm	0 mm
Observer 1		32	12.5
Observer 2		31	12.5
Observer 3		30	12.5
Observer 4		31	12.5
Observer 5		31	12.5
Observer 6		31	12.5
Observer 7		31	12.5
Observer 8		31	12.5
Observer 9		31	12.5
Observer 10		31	12.5
Observer 11		31	12.5
Observer 12		31	12.5
Observer 13		31	12.5
Observer 14		31	12.5
Observer 15		31	12.5
Observer 16		31	12.5
Observer 17		31	12.5
Observer 18		31	12.5
Observer 19		31	12.5
Observer 20		31	12.5
Observer 21		31	12.5
Observer 22		31	12.5
Observer 23		31	12.5
Observer 24		31	12.5
Observer 25		31	12.5
Observer 26		31	12.5
Observer 27		31	12.5
Observer 28		31	12.5
Observer 29		31	12.5
Observer 30		31	12.5



For comparison, Table 3.3-3 shows reading taken by two relatively experienced observers, both of whom had handled and used the instrument on two previous occasions. Experimental conditions were the same as described above except that the phosphor was excited by ultra-violet light and a larger range of brightness was covered. These observers likewise had uncorrected 20/20 or better vision and normal color perception.

As expected the reproducibility of brightness comparison readings by a single observer is far better than the perceptible brightness difference data of Figure 3.1-2, since we are using the halving method mentioned in Section 3.1(b). However the reproduction of the readings of one observer by another is less satisfactory. In Table 3.3-3 it is seen that observer S reads consistently higher than observer K by a fraction which increases as brightness decreases. Other experiments have shown the disagreement between these two observers is always in the same direction, and that the threshold of S is at a higher brightness, and radiation, than that of K. Similar relationships exist between the readings and thresholds of observers L and D (Table 3.3-2), the latter having the lower threshold. A mass of additional data would be required before generalizations along this line could be stated.

The experiment, Table 3.3-3 shows reading taken by two relatively experienced observers, each of whom had handled and used the instrument on two previous occasions. In general conditions were the same as described above except that the photophor was excited by ultra-violet light and a larger range of brightness was covered. These observers likewise had uncorrected 20/50 or better vision and normal color perception.

As expected the reproducibility of brightness comparisons was not as good as that of a single observer in the latter than the perceptible brightness difference data of Figure 3.1-2, since we are using the halving method mentioned in Section 3.1(b). However the reproduction of the readings of one observer by another is less satisfactory. In Table 3.3-3 it is seen that observer A reads consistently higher than observer B by a fraction which increases as brightness decreases. Other experiments have shown the disagreement between these two observers is always in the same direction, and that the threshold of A is at a higher brightness, and redaction, than that of B. Similar relationships exist between the readings and thresholds of observers I and B (Table 3.3-2), the latter having the lower threshold. A mass of additional data would be required before generalizations along this line could be stated.



TABLE 3.2-3

Brightness Measurements by Experienced Observers

(Ultra-violet excitation. Brightness in foot-lamberts)

Run	A	B	C	D	E	F
Observer S	$29 \times 10^{-4}$	$12.0 \times 10^{-4}$	$10.8 \times 10^{-4}$	$35.5 \times 10^{-5}$	$15.5 \times 10^{-5}$	$15 \times 10^{-6}$
29	21.3	12.5	45	14.2	19.5	
29.8	18.6	10.5	27	15.3	17.2	
30	20.7	12.2	51	17.7		
	12.7		46	14.0		
	29.0			13.1		
	18.7					
Mean	$29.4 \times 10^{-4}$	$19.0 \times 10^{-4}$	$11.5 \times 10^{-4}$	$14.9 \times 10^{-5}$	$14.9 \times 10^{-5}$	$17.2 \times 10^{-6}$
Standard Deviation	2%	14%	5%	12%	5%	9%
Observer K	$28 \times 10^{-4}$	$16.0 \times 10^{-4}$	$9.0 \times 10^{-4}$	$36 \times 10^{-5}$	$9.5 \times 10^{-5}$	$10.5 \times 10^{-6}$
24	15.5	9.5	34	7.0	10.5	
28	18.0	12.0	34	12.0	14.0	
27	16.5	12.8	40	13.0		
		11.0	31	10.0		
			27	12.5		
Mean	$26.7 \times 10^{-4}$	$16.5 \times 10^{-4}$	$10.9 \times 10^{-4}$	$33.6 \times 10^{-5}$	$10.6 \times 10^{-5}$	$11.7 \times 10^{-6}$
Standard Deviation	4%	4%	7%	6%	9%	16%
Ratio S/K	1.10	1.15	1.06	1.21	1.40	1.47





The limitations of the only available low-brightness standard have thus far thwarted a decisive demonstration of the lower limit of radiation at which reliable brightness readings can be obtained. However, the evidence at hand indicates that such a lower limit for a dark-adapted observer is well below 400 milliroentgens per hour. This estimate is based on the following considerations. The best phosphor disc produced to date in the work described in Chapter 4 is a 2-inch disc consisting of 9.7 grams of phosphor in a polystyrene binder. Its brightness under 40 mr/hr of radium gamma excitation, as measured by a type 5819 photo-multiplier<sup>5</sup> was  $1.2 \times 10^{-6}$  foot-lamberts, or one-tenth of the brightness readings shown in Column F of Table 3.3-3. Hence a radiation of 400 mr/hr is certainly measurable by brightness comparison.<sup>6</sup> However the improvement in detection threshold and arrow orientation brought about by a decrease in the phosphor-to-eye distance as shown in Table 3.3-1 is so spectacular as to permit a confident statement that some degree of improvement can also be made in brightness comparison by the same means. Another area in which improvement is to be expected is the manufacture of larger and more efficient phosphor discs than

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5. The photomultiplier calibration against the low-brightness meter is described in Appendix A.1.

6. The linearity of brightness response of  $\text{ZnCdS}(\text{Cu})$  with exciting intensity at room temperature over an intensity range of  $10^5$  has been demonstrated by Nail et al (N1).



The limitations of the only available low-brightness standard have thus far thwarted a decisive demonstration of the lower limit of radiation at which reliable brightness readings can be obtained. However, the evidence at hand indicates that such a lower limit for a dark-adapted observer is well below 400 milliwatts per hour. This estimate is based on the following considerations. The best phosphor disc produced to date in the work described in Chapter 4 is a 2-inch disc consisting of 9.7 grams of phosphor in a polyethylene binder. Its brightness under 40 mW of radiant energy excitation, as measured by a type 5012 photo-multiplier<sup>2</sup> was 1.2 x 10<sup>-6</sup> foot-lamberts, or one-tenth of the brightness readings shown in Column 7 of Table 3.3-3. Hence a radiation of 400 mW/hr is certainly measurable by brightness comparison. However, the improvement in detection threshold and error criterion brought about by a decrease in the phosphor-to-eye distance as shown in Table 3.3-1 is so appreciable as to permit a confident statement that some degree of improvement can also be made in brightness comparison by the same means. Another case in which improvement is to be expected in the manufacture of larger and more efficient phosphor discs than

2. The photo-multiplier excitation source used in the low-brightness work is described in Appendix A.1.

3. The linearity of brightness response of RCA 5012 (Co) with existing intensity at room temperature over an intensity range of 10<sup>3</sup> has been demonstrated by Hill et al. (1951).



are now available. Stating the possible lower limit as well below 400 mr/hr therefore seems quite conservative. The upper limit of the visual radiation meter, set by the saturation brightness of the phosphor, has not been explored, but the data of Table 3.3-2 and of the figure in Appendix A.1 show that it is greater than 100 roentgens per hour. An estimate of 1000 r/hr for this figure would be conservative.

Concerning the limitations on the use of a visual radiation meter in view of the thresholds for detection and successful brightness comparisons shown above, it is evident that dark adaptation of the observer will be a pre-requisite to radiation measurements near the measurement threshold, with the required degree of dark adaptation increasing as the minimum radiation to be measured decreases. As a result, an observer originally adapted to daylight, observing continuously as his dark-adaptation progresses, will be able to see levels of radiation in the vicinity of 10 roentgens per hour within a few seconds, but will require 15 to 20 minutes of dark adaptation before he will be able to detect 20 mr/hr, or to measure the order of 100 mr/hr. Dark adaptation time can of course be greatly decreased by pre-adaptation in red light through the use of red goggles, as now extensively used by those engaged in night navigation and gunnery in the armed services. Hulbert (H1) has shown that, while essentially complete dark



adaptation requires 21 minutes after exposure to 120 foot-candles of tungsten light, the required time is reduced to 7 minutes after exposure to the same intensity of red light (6500 Å°).



exposure 25 minutes after exposure to 100 foot-  
candle of blue light, the required time is reduced to  
7 minutes after exposure to the same intensity of red light

(6500 Å°).

## CHAPTER 4

### LUMINESCENT MATERIAL IN PLASTIC BINDER

#### 4.1. Phosphor-Plastic Mixtures.

The selection of a sulfide phosphor for use in the visual radiation meter was followed by a search for means to obtain the maximum brightness at the surface of a layer of phosphor. A review of the literature and inquiry among persons and companies interested in crystal growing revealed no source of zinc sulfide crystals of reasonable size, so attention was turned to improving the luminescent yield of the fine-grained zinc-cadmium sulfide which appeared to be the best readily obtainable phosphor for our purpose (Section 3.2).

The chief limitations on the light output from the surface of a given mass of this material and of the zinc sulfide phosphor family in general, arise from their small crystal size (1-50 microns), strong absorption of their own emitted light, and high index of refraction (for  $\text{ZnS}$ ,  $n = 2.356$ , and for  $\text{CdS}$ ,  $n = 2.506$ , both at  $5893 \text{ \AA}^0$ , ( $\text{H}_2$ ) ). Thus in thick layers of these small crystals, scattering of the light emitted from an interior crystal increases the probability of absorption before it reaches the surface where it can be seen. Furthermore, the high index of refraction and consequent small critical angle  $\sin^{-1} \frac{1}{n}$  for total internal

CHAPTER 4  
LUMINESCENT MATERIAL IN FLUORESCENT MINERAL

#### 4.1. Phosphor-Plastic Mixture.

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reflection at a crystal-air surface, mean that a large fraction of the light must make one or more reflections from a crystal-air surface before escaping from the crystal, hence absorption in this manner may also seriously reduce the potentially available light. (The crystals of several sulfide phosphors examined do not have perfectly regular shape, but have small striations on the crystal faces, so it is unlikely that a significant portion of the light would be permanently entrapped in the crystals due to internal reflection.) Thus it seemed reasonable that we might improve the total light output at the surface of a given mass of phosphor by simply filling the interstices between crystals with a material of refractive index matching or approaching that of the phosphor, provided such material is transparent to the emitted light. Thus we would at once increase the critical angle at the crystal surfaces, since it is given by  $\sin^{-1} (n'/n)$  (where  $n'$  is the refractive index of the less dense and  $n$  of the more dense medium), allowing a larger fraction of the generated light to escape from a crystal without total internal reflection, and decrease the reflection coefficient at each crystal boundary, since this coefficient depends, at normal incidence, on  $(n'-n)^2/(n'+n)^2$ .

A transparent plastic immediately suggests itself as a possible binder for the phosphor crystal powder. The use for other purposes of a transparent plastic binder for powdered crystalline sulfide phosphors has been reported pre-

reflection at a crystal-air surface, mean that a large fraction of the light must make one or more reflections from a crystal-air surface before escaping from the crystal, hence absorption in this manner may also seriously reduce the potentially available light. (The crystals of several solids phosphors examined do not have perfectly regular shape, but have small irregularities on the crystal faces, so it is unlikely that a significant portion of the light would be permanently trapped in the crystal due to internal reflection.) Thus it seemed reasonable that we might improve the total light output of the surface of a given mass of phosphor by etching the irregularities between crystals with a material of refractive index matching or approximating that of the phosphor, provided such material is transparent to the emitted light. This we would do once increase the critical angle at the crystal surface, since it is given by  $\sin^{-1}(n/n')$  (where  $n'$  is the refractive index of the less dense and  $n$  of the more dense medium), allowing a larger fraction of the generated light to escape from a crystal without total internal reflection, and decrease the reflection coefficient at each crystal boundary, since this coefficient depends, as is well known, on  $(n'-n)^2/(n'+n)^2$ .

A transparent plastic immediately suggests itself as a possible binder for the phosphor crystal powder. The use for other purposes of a transparent plastic binder for powdered crystalline solids phosphors has been reported pre-



viously. Frey (F1) used a thin paste of zinc sulfide and polystyrene spread directly on the envelope of an end-window photo-multiplier to count neutrons by luminescence of the zinc sulfide excited by recoil protons from the plastic.

Robinson and co-workers (R1, R2) have used similar thin mixtures of several inorganic phosphors and polystyrene to count alpha particles. Considerable attention has been given lately (S2, K3) to the use of organic phosphor materials dissolved in plastics of various kinds, obtaining large, clear, amorphous masses for counting neutrons and gamma-rays with high efficiencies at high counting rates.

We are here interested, however, in finding the optimum thickness, in grams per square centimeter, and the optimum proportion of plastic and phosphor, which will yield the brightest surface luminescence under gamma excitation, points on which little information has been available. Kallman (K2) has published curves showing total light output from phosphor screens as a function of thickness, under alpha and gamma excitation. His curve for  $\alpha$ -excitation is reproduced as Figure 4.1-1, where it is seen that the maximum light intensity from  $\text{ZnS}$ ,  $\text{Zn}_2\text{SiO}_4$ , and  $\text{CaWO}_4$  occurs at  $5 \text{ mgm/cm}^2$ , which according to Kallman is just the range of the alpha-particles used. Under gamma excitation, Figure 4.1-2, the light intensity does not appear to reach a maximum for any of these phosphors, but flattens out above  $50 \text{ mg/cm}^2$ , increasing only slightly for greater thicknesses. Kallman notes that this effect demon-



visually. They (21) need a thin piece of thin white and  
polyethylene window directly on the surface of an end-window  
photo-multiplier to prevent damage by ionization of the  
line window caused by recoil protons from the plastic.  
Nobleson and co-workers (21, 22) have used similar thin mix-  
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citation. His curve for excitation is reproduced as Figure  
4.1-1, where it is seen that the maximum light intensity from  
the  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{238}\text{U}$  sources at 5  $\text{m}\mu\text{m}^2$ , which according  
to Kallman is just the range of the alpha-particles used. Un-  
der gamma excitation, Figure 4.1-2, the light intensity does  
not appear to reach a maximum for any of these phosphors, but  
flattens out above 20  $\text{m}\mu\text{m}^2$ , increasing only slightly for  
greater thicknesses. Kallman notes that this effect demon-

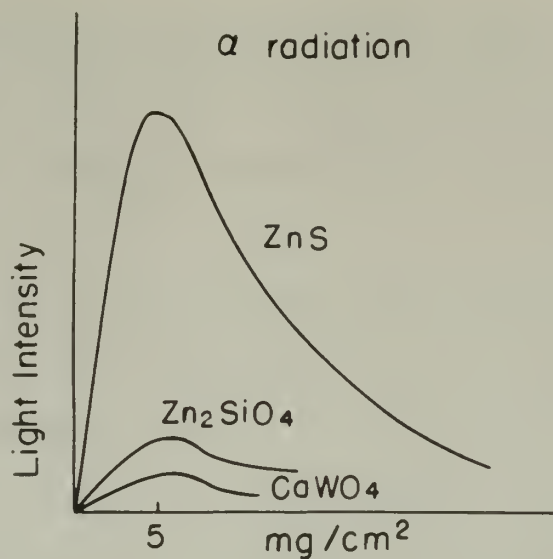


Figure 4.1-1 LUMINESCENT LIGHT INTENSITY AS A FUNCTION OF PHOSPHOR THICKNESS. ALPHA EXCITATION. (Kallman, Ref. K2)

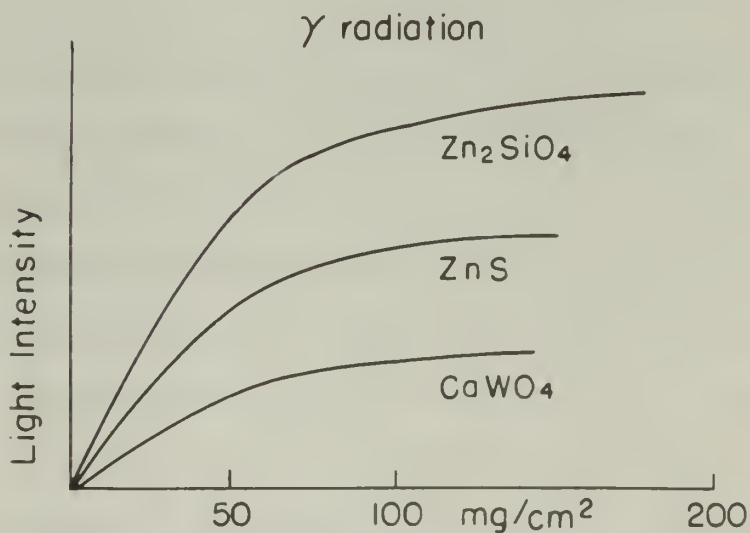


Figure 4.1-2 LUMINESCENT LIGHT INTENSITY AS A FUNCTION OF PHOSPHOR THICKNESS. GAMMA EXCITATION. (Kallman, Ref. K2)





strates that these materials do absorb the emitted light, since the gamma radiation used was sufficiently hard that no appreciable absorption of the gammas took place in the phosphor.

(The relative light outputs of  $\text{Zn}_2\text{SiO}_4$  and  $\text{ZnS}$  under alpha and gamma excitation as shown appear to be incompatible. Generally, it would be expected that relative efficiencies of two phosphors would not change greatly under different excitation. Such a view is supported by efficiency data on these two phosphors published by Kallman in two different reports (B1, B2), showing that the sulfide is more efficient than the silicate under  $\alpha, \gamma$ , and x-ray excitation, and by the experimental results reported in Section 3 of this chapter. Hence it is reasonable to suspect that the labels of the curves for  $\text{Zn}_2\text{SiO}_4$  and  $\text{ZnS}$  in Figure 4.1-2 have been interchanged by error.)

These curves by Kallman furnish an additional reason for using a plastic binder for the powdered phosphor. Since we are interested in maximum brightness of the phosphor surface, under gamma-ray excitation, we evidently must use thicknesses of sulfide phosphor greater than  $0.1 \text{ mg/cm}^2$  (Figure 4.1-2, curve for  $\text{ZnS}$ ). The plastic binder appears to be a convenient means of obtaining a homogeneous surface in such large thicknesses, provided no loss of brightness results from introduction of the plastic.

states that these materials do absorb the emitted light, since the gamma radiation used was sufficiently hard that no appreciable absorption of the gammas took place in the phosphor.

(The relative light outputs of  $\text{BaF}_2$  and  $\text{CaF}_2$  under alpha and gamma excitation as shown appear to be incompatible. Generally, it would be expected that relative efficiencies of two phosphors would not change greatly under different excitation. Such a view is supported by efficiency data on these two phosphors published by Kallman in two different reports (SI, K2), showing that the sulfide is more efficient than the silicate under  $\alpha$ ,  $\gamma$ , and x-ray excitation, and by the experimental results reported in Section 3 of this chapter. Hence it is reasonable to suspect that the labels of the curves for  $\text{BaF}_2$  and  $\text{CaF}_2$  in Figure 4.1-2 have been interchanged by error.)

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#### 4.2. Manufacture of Phosphor-Plastic Mixtures.

Selection of the plastic materials for use in these experiments was necessarily based on their working properties and availability as well as their optical properties. The plastics finally selected were a methacrylate<sup>1</sup> (Lucite) and a polystyrene<sup>2</sup>, with refractive indices (in yellow light) of 1.50 and 1.59 respectively, the latter being relatively high among the transparent plastics. The lucite was obtained in the form of a compression-molding powder, the polystyrene as a monomer casting liquid, polymerized by heating after the addition of a small amount of catalyst (benzoyl peroxide with 6% active oxygen) and an accelerator (methylene chloride). Both these plastics are nearly transparent in the visual range (R6), with a transmission greater than 85% in the emission bands of  $\text{Zn-CdS}(\text{Cu})$  and  $\text{Zn}_2\text{SiO}_4$  (Mn) (Figures 3.2-1, 2).

The first experiments were made with the polystyrene casting liquid. The technique used for manufacturing discs of any desired phosphor-plastic proportion is a simple one briefly described as follows:

Weigh into a glass mold the desired amount of casting liquid and add one drop of catalyst for each 3 grams of plastic. Stir vigorously with glass rod to distribute the catalyst. Add the desired weight of phosphor by sprinkling

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1. "Transoptic" Molding Powder, Buehler and Co., Ltd., Chicago, Ill.

2. "Fellowcast," Fellowcrafters, Inc., Boston, Mass.



4.3. Preparation of Phosphor-Plastic Mixtures.

Selection of the plastic materials for use in these experiments was necessarily based on their working properties and availability as well as their optical properties. The plastic finally selected was a methacrylate<sup>1</sup> (Lucite) and a polystyrene<sup>2</sup>, with refractive indices (in yellow light) of 1.50 and 1.59 respectively, the latter being relatively high among the transparent plastics. The Lucite was obtained in the form of a compression-molding powder, the polystyrene as a solvent-casting liquid, polymerized by heating after the addition of a small amount of catalyst (benzoyl peroxide) with 6% active oxygen, and an accelerator (azobisisobutyronitrile). These plastics are nearly transparent in the visual range (400 mμ), with a transmission greater than 85% in the ultraviolet (200 mμ) and in the infrared (10 mμ) (Figures 3-1, 3-2). The three experiments were made with the polystyrene casting liquid. The technique used for manufacturing discs of any desired phosphor-plastic proportion is a simple one briefly described as follows:

Weigh into a glass mold the desired amount of casting liquid and add one drop of catalyst for each 2 grams of plastic. Stir vigorously with glass rod to distribute the catalyst. Add the desired weight of phosphor by sprinkling,

1. "Methacrylate" Molding Powder, Badger and Co., Ltd., Chicago, Ill.
2. "Polystyrene", Polystyrene, Inc., Boston, Mass.

it over the surface of the casting liquid and stir until a uniform paste is obtained. Add 1 drop of accelerator per 3 grams of plastic and stir again to distribute the accelerator (a slightly larger proportion of accelerator may be necessary for mixtures with a phosphor to plastic weight ratio of 2 or higher). Allow to stand for about 10 minutes at room temperature, then place in oven at  $92^{\circ}\text{C}$  for about 1 hour (longer for large phosphor/plastic ratios). Cool slowly to room temperature. The mixture contracts slightly upon solidifying so that it can readily be removed from the mold.

The discs so obtained when glass culture dishes were used as molds had a glossy top surface, but the bottom and sides in contact with the glass during molding had a dull finish which could be polished on a metallographic specimen polishing wheel. The principal defect of the discs so prepared was that the phosphor/plastic ratio was not uniform through a cross-section, the heavy sulfide powder having a marked tendency to settle to the bottom of the mold through the viscous liquid. This effect introduced an uncertainty regarding the effective phosphor/plastic ratio at the top and bottom surfaces when the total light output was to be measured in a series of discs with varying overall proportions of phosphor to plastic. For this reason we turned to the use of lucite molding powder with which it was found that



is over the surface of the casting liquid and stir until a uniform paste is obtained. Add 1 drop of accelerator per 1 gram of plastic and stir again to distribute the accelerator (a slightly larger proportion of accelerator may be necessary for mixtures with a pronounced plastic weight ratio of 2 or higher). Allow to stand for about 10 minutes at room temperature, then place in oven at 220°C for about 1 hour (longer for large phosphor/plastic ratios). Cool slightly to room temperature. The mixture contracts slightly upon solidifying so that it can readily be removed from the mold.

The discs as obtained when glass culture dishes were used as molds had a glossy top surface, but the bottom and sides in contact with the glass during molding had a dull finish which could be polished on a metallographic speed-see polishing wheel. The principal defect of the discs so prepared was that the phosphor/plastic ratio was not uniform through a cross-section, the heavy buildup powder having a marked tendency to settle to the bottom of the mold through the viscous liquid. This effect introduced an uncertainty regarding the effective phosphor/plastic ratio at the top and bottom surfaces when the total light output was to be measured in a series of discs with varying overall proportions of phosphor to plastic. For this reason we turned to the use of loose molding powder with which it was found that



quite homogeneous discs can be made at ratios less than 3.0 if sufficient attention be paid to the mixing in the procedure described below. This virtue of the lucite powder was considered to offset the disadvantage of its smaller index of refraction at least for the purpose of determining the optimum phosphor/plastic ratio; as will be seen later a polystyrene mixture produced the most efficient phosphor disc.

The lucite-phosphor mixtures were molded under pressure supplied by a small hydraulic press designed for embedding metallographic specimens in plastic. The first phosphor discs were made in a 1" diameter mold but for visual observation a larger size was desirable, and a 1 7/16" mold was used for all the later work.<sup>3</sup> The mold consists of a cylindrical steel sleeve with wall designed to withstand 5000 Psi, closed at the bottom by a removable steel plug, and at the top by a steel plunger through which the pressure was applied. A hole was drilled through the plunger to within 3/8 in. of the bottom, to receive a thermometer. The bottom plug and the plunger fit the sleeve with a tolerance of 0.001 inch to prevent appreciable extrusion between the moving parts, and all inner surfaces of the mold were ground to a smooth finish. To heat the mold, a heating jacket was made consisting of a cylindrical aluminum shell with inner diameter fitting the

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3. This size was not chosen by design, but was the diameter of an available mold, previously used locally for another purpose, which could be modified for the present application. It is recognized that larger discs would be advantageous.

This also was not chosen by design, but was the diameter of an available mold, previously used locally for another purpose, which could be modified for the present application. It is recognized that larger diameters would be advantageous.



steel sleeve of the mold loosely. A coil of nichrome wire, insulated with asbestos, was wound inside the shell as the heating element. With this equipment, the following procedure was used in making phosphor-plastic discs:

Weigh the desired amounts of phosphor and plastic onto weighing paper. Mix thoroughly with spatula. After cleaning all inner surfaces of the mold with alcohol or acetone, pour the plastic-phosphor mixture into mold with bottom plug in place, and mix again in the mold. Insert plunger, place assembled mold in press and apply 100 psi to remove air. Release pressure, heat to  $110^{\circ}\text{C}$ ; apply 3000 psi, heat to  $140^{\circ}\text{C}$ . Cool rapidly to  $90^{\circ}\text{C}$ , force out plunger and plug with completed phosphor disc.

This procedure produced homogeneous phosphor-plastic discs with ratios up to 3.0. At larger ratios it was difficult to prevent inhomogeneities, and beyond 4.0 the surfaces invariably showed local areas containing little or no plastic so that the phosphor was easily chipped off. At ratios below 3.5 the surfaces were ordinarily smooth and well-polished. In all, about 65 discs were made with this procedure, though only about half of these were of value in obtaining the results of the next section.

#### 4.3. Experiments with Phosphor-Plastic Mixtures.

##### (a) Experimental Equipment.

The point of departure for the phosphor-plastic



steel sleeve of the mold assembly. A coil of nichrome wire, insulated with asbestos, was wound inside the shell on the heating element. With this equipment, the following procedure was used in making phosphor-plastic discs: Weigh the desired amount of phosphor and plastic onto weighing paper. Mix thoroughly with spatula. After cleaning all inner surfaces of the mold with alcohol or acetone, pour the plastic-phosphor mixture into mold with bottom plug in place, and mix again in the mold. Insert plunger, place assembled mold in press and apply the psi to remove air. Release pressure, heat to 110°C; apply 1000 psi, heat to 140°C. Cool rapidly to 90°C, remove end plunger and plug with completed phosphor disc.

This procedure produced homogeneous phosphor-plastic discs when ratios up to 3.0. At higher ratios it was difficult to prevent inhomogeneity, and beyond 4.0 the whiskers invariably formed loose areas containing little or no phosphorus. As the phosphor was easily abraded off, the ratios below 3.5 the discs were relatively smooth and well polished. In all, about 65 discs were made with this procedure, though only about half of these were of value in obtaining the results of the heat treatment.

#### 4.3. Experiments with Phosphor-Plastic Mixtures

##### (a) Experimental Equipment

The goal of experiments for the phosphor-plastic

mixture experiments was to determine the thickness of phosphor alone which would provide the greatest light yield under gamma and beta excitation. For this purpose, and for phosphor disc measurements, equipment was arranged to measure the brightness of a phosphor screen on one surface while the exciting radiation was applied to the opposite surface, following the procedure used by Hallman (K2).

A Type 5819 photomultiplier tube was mounted in a brass light shield with a cardboard ( $0.13 \text{ gm/cm}^2$ ) light-tight top which was readily removable for easy access to the end-window. The tube was protected with a magnetic shield, and operated at 75 volts per dynode from a stabilized negative high-voltage supply. Anode current from the 5819 tube was measured by a Beckman micro-microammeter for currents up to  $10^{-7}$  amperes, and by a Beta microammeter for larger currents.

The stability of this system was such that a reference current reading, established early in the work, consisting of a reference phosphor disc excited by a small radium source placed at a fixed distance from the phosphor, could be repeated at will within less than 4% over a period of seven weeks. Provision was made for adjusting the photo-multiplier voltage to compensate for changes in the reference reading due to drift, line voltage changes, etc., but this was necessary on only two occasions. Under these conditions of photo-multiplier operation, fatigue effects and noise current were



multiplier operation, fatigue effects and some constant were  
try on only two occasions. Under these conditions of photo-  
due to effect, time voltage changes, etc., but this was neces-  
sary to compensate for changes in the reference reading  
weeks. Variation was made for adjusting the photo-multiplier  
response as well as the time interval over a period of seven  
months passed at a fixed distance from the multiplier, could be  
that of a reference frequency also varied by a small reading  
some present reading, associated with it in the work, consist-  
The stability of this system was such that a refer-



not noticeable. The arrangement described was used for all phosphor light output measurements reported in this chapter. Conversion of photo-multiplier anode current to an approximate figure for phosphor brightness in foot-lamberts was accomplished by the calibration procedure described in Appendix A.1.

(b) Light Yield of Phosphor Powder.

The phosphor powder was placed in a cylindrical aluminum cell with thin glass bottom resting directly on the end-window of the phototube. The inside diameter of the cell was 1.406 inches, slightly less than the minimum specified diameter (1.5 inches) of the photo-cathode, and closely matching the diameter of the most frequently used size of phosphor-plastic discs, 1.436 inches. (Care was taken to place the cell and the discs in a constant position on the cathode, and a 1.5 inch mask on the end-window was used as a guide for this purpose. Anode current reading is not critical for variations in placement of less than 0.1 inches.) The phosphor was irradiated by a 10 mg. (8.8 mrhm) radium gamma source (calibrated by the Bureau of Standards) placed at 45 cm from the face of the cathode. Current response of the phototube as a function of source distance followed an inverse square law at distances greater than about 30 cm from the phototube, hence the gamma radiation at the phosphor was equivalent to approximately

$$8.1 \times \frac{10^4}{(45)^2} = 40 \text{ mr/ hr.}$$

not noticeable. The arrangement described was used for all  
photograph light output measurements reported in this chapter.  
Correction of photo-multiplier noise current as an average  
value figure for photomultiplier is not indicated in ap-  
pendix A.1.

(b) Light Wave of Photomultiplier

The phosphor powder was placed in a cylindrical  
aluminum cell with thin glass bottom resting directly on the  
end-window of the phototube. The inside diameter of the cell  
was 1.406 inches, slightly less than the minimum specified  
diameter (1.5 inches) of the photo-cathode, and closely  
matching the diameter of the most frequently used size of  
phosphor-plastic discs, 1.406 inches. Care was taken to  
place the cell and the disc in a constant position on the  
cathode, and a 1.5 inch mark on the end-window was used as  
a guide for this purpose. No exact reading is not  
critical for variations in placement of less than 0.1 inches.  
The phosphor was irradiated by a 10 mμ (2.5 mμ) region  
germ source (calibrated by the Bureau of Standards) placed  
at 45 cm from the face of the cathode. Current response of  
the phototube as a function of source distance followed an  
inverse square law at distances greater than about 30 cm  
from the phototube, hence the same rotation at the photo-  
tube was equivalent to approximately

$$6.1 \times \frac{10^4}{(42)^2} = 40 \text{ mμ / hr.}$$



The light yield of two phosphor materials as a function of thickness under these conditions is shown in Figure 4.3-1. For Zn-CdS(Cu), the maximum yield is reached at  $0.9 \text{ gm/cm}^2$  of phosphor, decreasing slowly at greater thicknesses due to gamma ray absorption in the upper layers of phosphor. The general shape of the  $\text{Zn}_2\text{SiO}_4$  curve is the same, but due to its much smaller efficiency and the opacity of the crystals to the emitted light, the maximum light yield is less than one-fifth that of the sulfide and occurs at much smaller thickness.

A similar experiment using beta-ray excitation from a strontium-90 source produced the curves shown in Figure 4.3-2, where the opacity and smaller efficiency of the orthosilicate produce effects relative to the sulfide similar to those found under gamma excitation. The peak light yield occurs in Zn-CdS(Cu) at about  $0.2 \text{ gm/cm}^2$ . If to this is added the absorber thickness traversed by the betas before reaching the phosphor (a total of  $0.16 \text{ gm/cm}^2$ ), it is seen that the peak corresponds closely with the  $0.38 \text{ gm/cm}^2$  range of beta particles having the average energy (0.92 Mev) of the yttrium-90 beta spectrum (E1, E3). For the  $\text{Zn}_2\text{SiO}_4$ , the maximum light yield occurs at smaller thickness because of absorption of the light emitted in the upper layers of phosphor.

Beyond noting that the general shapes of the individual curves are similar to those given by Kallman under photon and charged-particle excitation, it is difficult to attempt



The light yield of two phosphor materials as a function of thickness under these conditions is shown in Figure 4.3-1. For Zn-Ge(Cu), the maximum yield is reached at 0.9  $\mu\text{m}$  of phosphor, decreasing slowly as greater thicknesses due to gamma ray absorption in the upper layers of phosphor. The general shape of the  $\text{Zn-Ge(Cu)}$  curve is the same, but due to its much smaller efficiency and the opacity of the crystals to the emitted light, the maximum light yield is less than one-fifth that of the sulfide and occurs at much smaller thicknesses. A similar experiment using beta-ray excitation from strontium-90 sources produced the curves shown in Figure 4.3-2, where the opacity and smaller efficiency of the orthosulfides produce effects relative to the sulfide similar to those found under gamma excitation. The peak light yield occurs in Zn-Ge(Cu) at about 0.2  $\mu\text{m}$ . If so, this is added the absorber thickness traversed by the beta rays reaching the phosphor (a total of 0.16  $\mu\text{m}$ ), is the same with the peak corresponds closely with the 0.34  $\mu\text{m}$  range of beta particles having the average energy (0.97 MeV) of the strontium-90 beta spectrum (Fig. 4.3). For the  $\text{Zn-Ge(Cu)}$ , the maximum light yield occurs at smaller thicknesses because of absorption of the light emitted in the upper layers of phosphor. Beyond noting that the general shapes of the individual curves are similar to those given by Lohman under photon and charged-particle excitation, it is difficult to associate

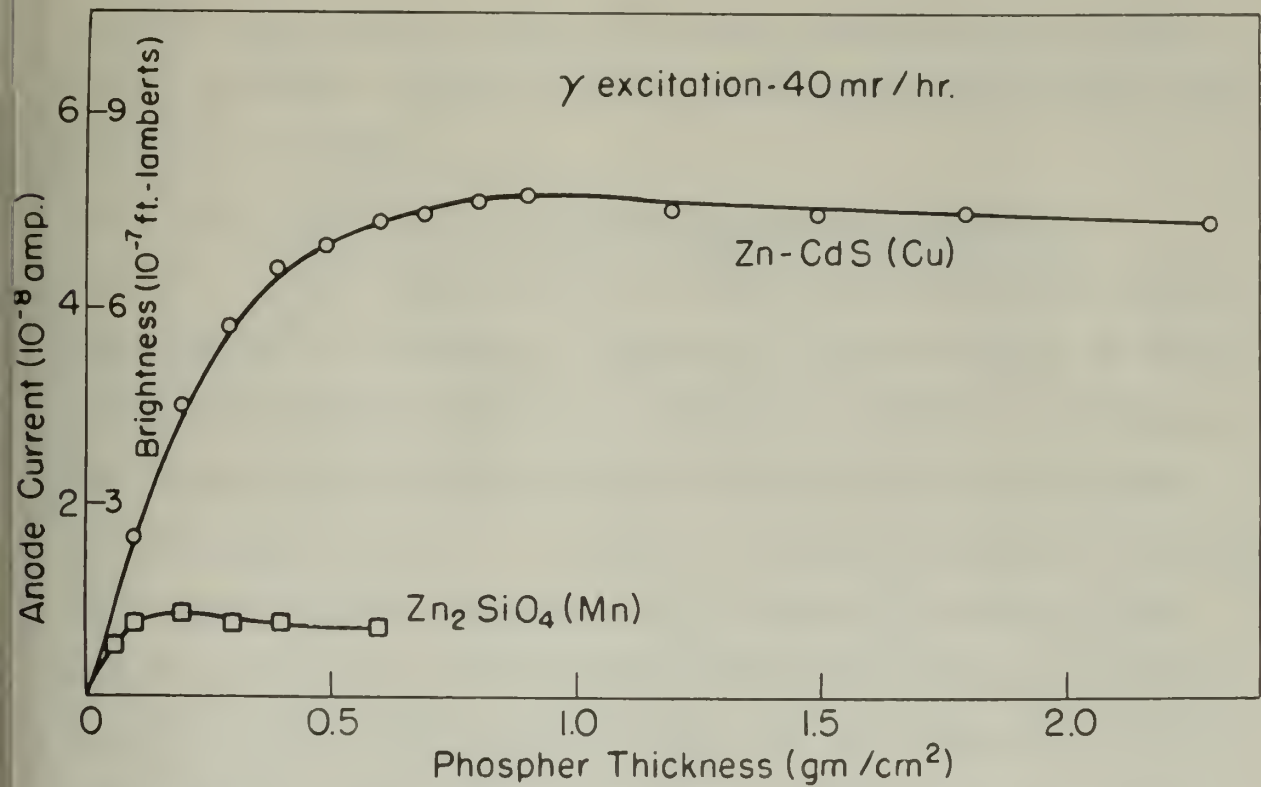


Figure 4.3-1 LIGHT YIELD AS A FUNCTION OF PHOSPHOR THICKNESS. GAMMA EXCITATION.

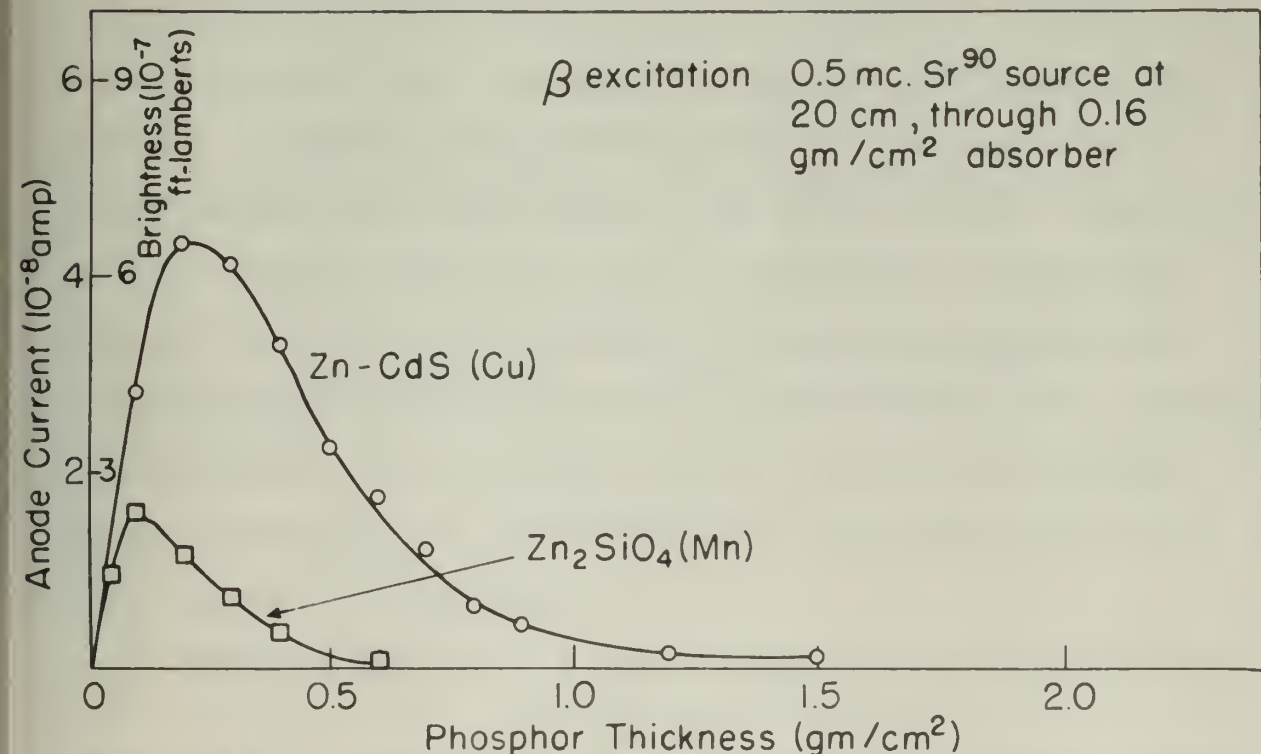


Figure 4.3-2 LIGHT YIELD AS A FUNCTION OF PHOSPHOR THICKNESS. BETA EXCITATION.





to draw comparisons, since the exact constitution and form of the phosphor screens and the sources of radiation he used were not reported.

(c) Light Yield of Phosphor-Plastic Mixtures.

The light yield as a function of phosphor thickness ( $\text{gm}/\text{cm}^2$ ) is shown in Figure 4.3-3 for a series of phosphor-lucite discs containing increasing amounts of phosphor but with a constant proportion of phosphor to lucite given by the weight ratio  $R = 2$  (grams of phosphor/grams of lucite). (The light yields plotted are the average readings of the two flat surfaces, to compensate for small inhomogeneities. The two readings ordinarily differ by less than 7%.) At small thicknesses it is seen that the light yield parallels that of the phosphor powder alone, which is re-drawn here for comparison from Figure 4.3-1, but reaches a maximum at about  $0.8 \text{ gm}/\text{cm}^2$ , and declines for greater thickness. This decline is interpreted as the result of increased loss of light emitted from the sides of the disc as linear thickness of the disc and hence area of the cylindrical surface increases, as well as the result of increased absorption of light, primary gammas, and secondary radiation by the plastic. (The response of clear lucite discs to gamma radiation has been measured and is of the order of 0.01 times that of the same weight of phosphor.)

That the ratio  $R = 2$  used in the series of Figure 4.3-3

to draw conclusions, since the exact concentration and form of the phosphor screen and the nature of radiation are used were not reported.

(c) Light Yield of Thorium-Yttrium Phosphor.

The light yield as a function of phosphor thickness ( $\text{gm/cm}^2$ ) is shown in Figure 4.3-3 for a series of phosphor-plate discs containing increasing amounts of phosphor but with a constant proportion of thorium to yttrium given by the weight ratio  $R = 2$  (grams of phosphor/grams of yttrium). (The light yields plotted are the average readings of the two first surfaces, so compensated for small inhomogeneities. The two readings ordinarily differ by less than 7%.) At small thicknesses it is seen that the light yield parallels that of the thorium powder alone, which is re-drawn here for comparison from Figure 4.3-1, but reaches a maximum of about  $0.8 \text{ gm/cm}^2$ , and declines for greater thickness. This decline is interpreted as the result of increased loss of light emitted from the sides of the disc as linear thickness of the disc and hence area of the cylindrical surface increases, as well as the result of increased absorption of light, primarily gamma, and secondary radiation by the plastic. (The response of clear yttrium discs to gamma radiation has been measured and is of the order of 0.01 times that of the same weight of phosphor.) Thus the ratio  $R = 2$  used in the series of Figure 4.3-3

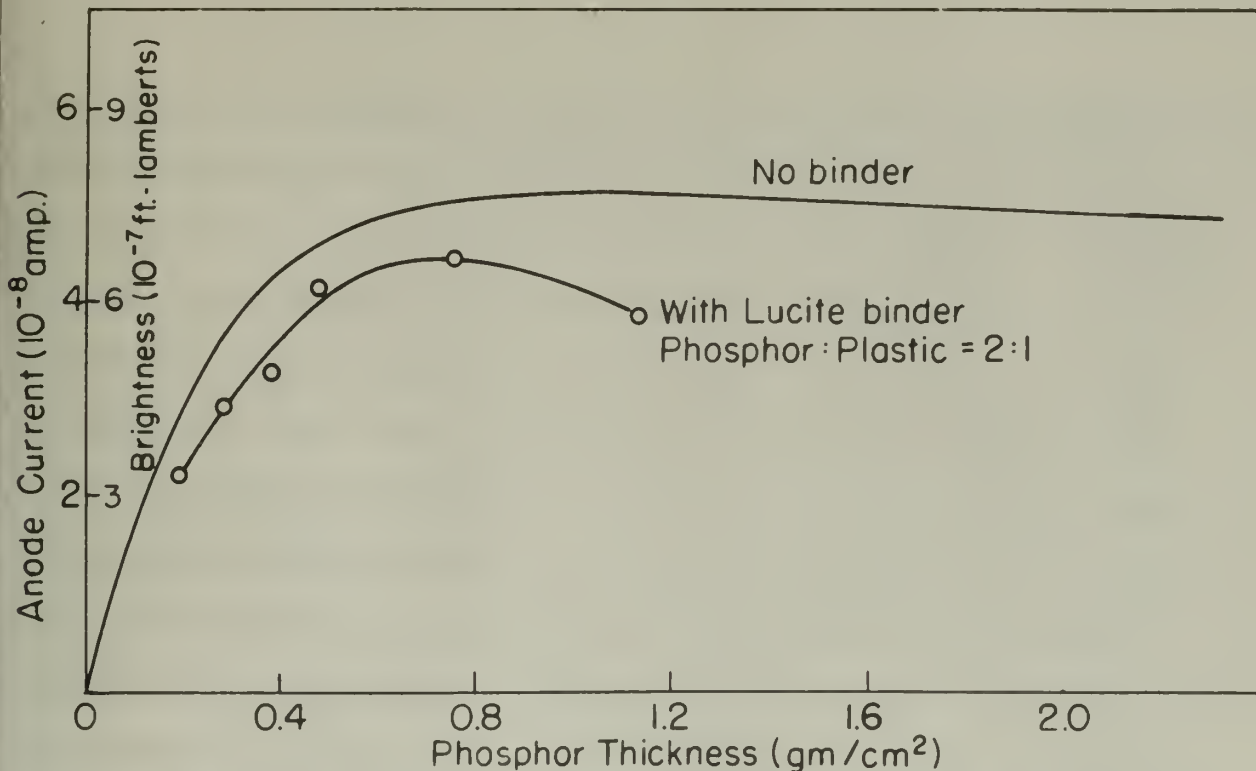


Figure 4.3-3 LIGHT YIELD AS A FUNCTION OF Zn-CdS (Cu) PHOSPHOR THICKNESS, WITH OR WITHOUT LUCITE BINDER. GAMMA EXCITATION.

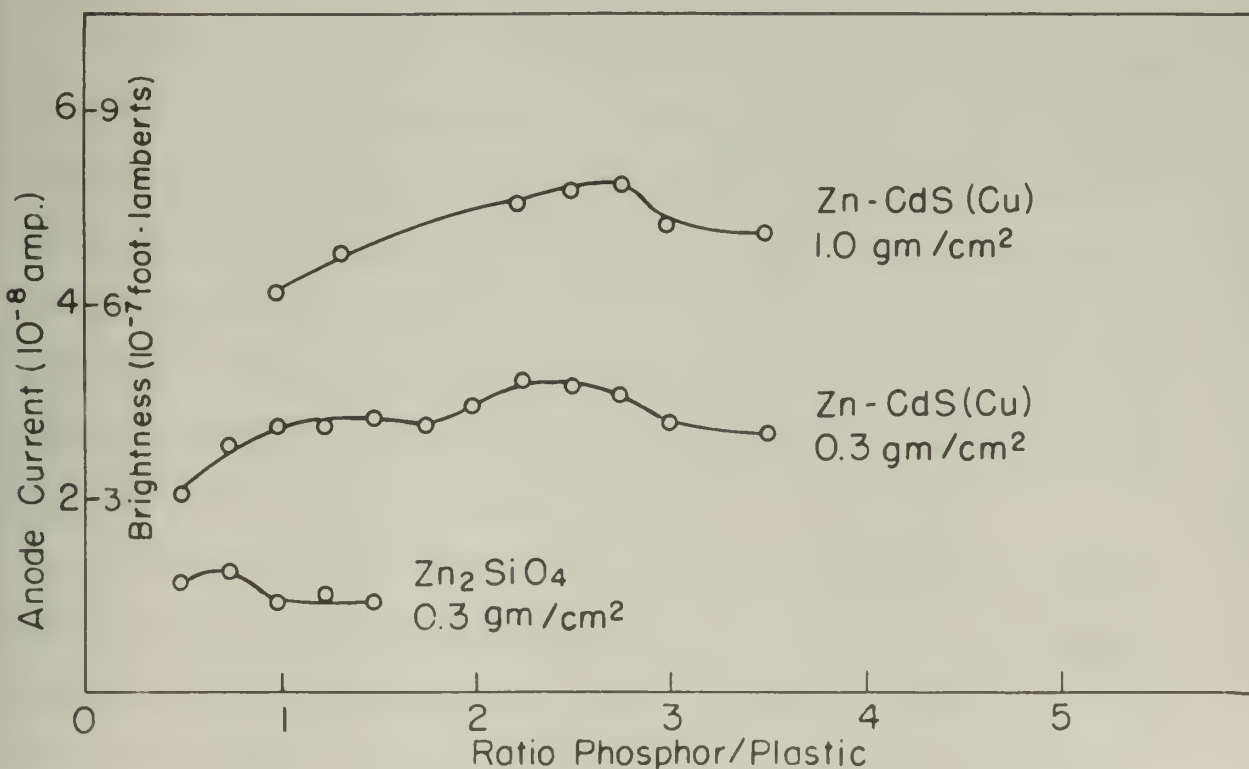


Figure 4.3-4 LIGHT YIELD AS A FUNCTION OF PHOSPHOR/ PLASTIC RATIO BY WEIGHT. GAMMA EXCITATION.





is below the optimum is shown in Figure 4.3-4, where light yield is plotted as a function of phosphor/plastic ratio  $R$  for two series of sulfide-lucite discs with constant phosphor thicknesses, showing that the optimum ratio appears to be about 2.75, for  $1.0 \text{ gm/cm}^2$  of phosphor, and about 2.25 for  $0.3 \text{ gm/cm}^2$ . The curve for  $1.0 \text{ gm/cm}^2$  phosphor includes the most efficient phosphor-lucite discs prepared to date, but it is noteworthy that the light yield from the best of these is slightly but not significantly higher than the maximum reached with the phosphor powder alone. We can say only that, at the optimum ratio and thickness ( $R = 2.75$ , thickness  $1.0 \text{ gm/cm}^2$ ) found to date, the additional light which is brought to the surface by the lucite binder is nearly offset by the other effects mentioned above.

Also shown in Figure 4.3-4 is a curve for  $\text{Zn}_2\text{SiO}_4$  with constant phosphor thickness  $0.3 \text{ gm/cm}^2$ . The maximum light output at  $R = 0.75$  is about 40% greater than the maximum obtained from the phosphor alone as shown in Figure 4.1-1. At ratios greater than 1.5 there is insufficient lucite to bind the very fine phosphor powder together. In view of the poor efficiency of this material compared to the sulfide, no further work with it was undertaken.

Turning to the use of polystyrene, which has a larger index of refraction than lucite, we have found a remarkable improvement over the performance of lucite, as indicated by the results in Table 4.3-1. The table gives the thickness

is below the optimum is shown in Figure A.3-4, where light yield is plotted as a function of phosphor/plastic ratio R for two series of alkylidene-luciferase discs with constant phosphor thickness, showing that the optimum ratio appears to be about 2.75 for 1.0 gm/cm<sup>2</sup> of phosphor, and about 4.25 for 0.3 gm/cm<sup>2</sup>. The curve for 1.0 gm/cm<sup>2</sup> phosphor includes the most efficient phosphor-luciferase discs prepared to date, but it is noteworthy that the light yield from the best of these is slightly but not significantly higher than the maximum reached with the phosphor powder alone. We can say only that, at the optimum ratio and thickness (R = 2.75, thickness 1.0 gm/cm<sup>2</sup>) found to date, the additional light which is brought to the surface by the lucifer binder is nearly offset by the other effects mentioned above.

Also shown in Figure A.3-4 is a curve for the light yield with constant phosphor thickness 0.3 gm/cm<sup>2</sup>. The maximum light output at R = 0.75 is about 40% greater than the maximum obtained from the phosphor alone as shown in Figure A.1-1. At ratios greater than 1.5 there is insufficient lucifer to bind the very fine phosphor powder together. In view of the poor efficiency of this material compared to the alkylidene, no further work with it was undertaken.

Turning to the use of polyethylene, which has a larger index of refraction than lucifer, we have found a remarkable improvement over the performance of lucifer, as indicated by the results in Table A.3-1. The table gives the thickness



of phosphor and ratio of phosphor to plastic for each of three phosphors made of Zn-CdS(Cu) and polystyrene, with their light output in terms of anode current from the phototube, under the same conditions used for the measurements on the lucite mixtures. (Although these particular discs were 2 inches in diameter, a 1 1/2 inch mask over the photo-cathode permits comparison with the measurements on the 1 7/16 inch discs.) It will be noted that the maximum light yield here is more than 30% greater than the best value obtained with powdered or lucite-bound phosphor, and that this maximum occurs at a phosphor/plastic ratio very close to the optimum ratio found for lucite mixtures.

TABLE 4.3-1

POLYSTYRENE AND Zn-CdS(Cu) MIXTURES

No.	Phosphor Thickness (gm/cm <sup>2</sup> )	Overall Ratio Phosphor/Plastic	Anode Current (10 <sup>-8</sup> amperes) and 1 1/2 inch diameter sur- face.	
			top face	bottom face
1	0.29	0.58	5.0	5.3
2	0.49	2.85	8.0	6.95
4	0.61	3.75	6.60	6.55

In the case of the polystyrene discs, as mentioned previously, a means of ensuring that the phosphor and plastic remain homogeneously mixed in the finished product has not yet been worked out. For this reason, the top surface of

of phosphor and ratio of phosphor to plastic for each of three phosphor sets of 20-25(Cu) and polyethylene, with each light output in terms of average output from the phosphor, under the same conditions used for the measurements on the plastic material. (Although these particular data were 2 inches in diameter, a 1 1/2 inch size over the phosphor-plastic composition with the measurements on the 1 5/16 inch glass.) It will be noted that the maximum light yield here is more than 30% greater than the best value obtained with powdered or fused-bond phosphor, and that this value occurred at a phosphor/plastic ratio very close to the optimum ratio found for fused material.

TABLE A-3-1

POLYETHYLENE AND 20-25(Cu) MIXTURES

Phosphor Thickness Overall Ratio  
 (mm) (mm) (mm)  
 1 0.25 0.25 1.00  
 2 0.49 0.49 2.00  
 4 0.98 0.98 4.00

1 0.25 0.25 1.00  
 2 0.49 0.49 2.00  
 4 0.98 0.98 4.00

In the case of the polyethylene glass, as mentioned previously, a means of measuring the phosphor and plastic yields homogeneously placed in the material would have not the best worked out. For this reason, the top surface of



disc No. 1 listed in Table 4.3-1 is almost clear plastic, the bottom being greatly enriched in phosphor. As a result, it might be anticipated that the brightness reading of the top surface would be smaller than that of the bottom (excitation in each case being directed at the opposite face, as usual), because the effective phosphor/plastic ratio at the bottom is closer to the optimum ratio, and the readings confirm this. In No. 2, the smaller proportion of polystyrene prevented as large a phosphor density gradient from bottom to top as shown by No. 1, but the bottom is definitely richer in phosphor than the top, and it is the top surface of No. 2 which yields the largest brightness reading, under the standard excitation (gamma radiation, 40 mr/hr) of all the phosphors tested. Since the overall ratio of phosphor to plastic in the disc is very close to the optimum ratio found for lucite mixtures with the same phosphor (Figure 4.3-4 upper curve), it follows that the effective ratio at the bottom surface is greater than the optimum, while the effective top ratio is less than optimum. Thus the upper region of this disc, where the phosphor crystals are relatively more widely spaced, makes its contribution to the high surface brightness and also permits efficient transmission of the light generated in the interior region of optimum ratio to the top surface, while the region near the bottom has the crystals too closely packed to permit such efficient transmission and furthermore its higher than optimum ratio of



also No. 1 listed in Table 4.7-1 is almost clear plastic, the bottom being greatly enriched in phosphorus. In a similar manner it might be anticipated that the phosphorus content of the top surface would be similar with that of the bottom (and bottom in such cases being situated at the opposite face, as usual). However the effective phosphorus ratio of the bottom is closer to the optimum ratio, and the resulting composition is also. In No. 2, the similar proportion of phosphorus suggested we have a phosphorus density gradient from bottom to top as shown by No. 1, but the bottom is relatively richer in phosphorus than the top, and it is the top surface of No. 2 which yields the largest phosphate reaction, under the standard conditions (same reaction, 40 ex/hr) at all the phosphorus levels. Since the overall ratio of phosphorus to plastic in the film is very close to the optimum ratio found for these mixtures with the same phosphorus (Table 4.7-1 upper group), it follows that the effective ratio of the bottom surface is greater than the optimum, while the effective top ratio is less than optimum. Thus the upper region of this film, where the phosphorus crystals are relatively more widely spaced, makes its contribution to the high rate of brightness and also provides efficient transmission of the light generated in the interior region of optimum ratio as the top surface, while the region near the bottom has the opposite top density gradient so that it would contribute to the brightness and transmission of the light from optimum ratio of

phosphor to plastic means that it is in the region of  $R = 3$  or higher, where its light yield is sharply below that of the optimum, a characteristic shown by all three curves of Figure 4.3-4. Finally, inspection of disc No. 4 (No. 3 is a clear plastic control disc) with an overall ratio much higher than the optimum, shows that it has a density gradient that is smaller than that of No. 2, but still perceptible. It is therefore unlikely that the effective ratio of phosphor to plastic at the top could be at or below optimum, and this is borne out by the brightness readings as shown.

The better performance of polystyrene as a binder, as compared to lucite, must be attributed largely if not entirely to its higher index of refraction, more closely approaching that of the sulfide phosphor. The polystyrene itself does not make an appreciable contribution to the light yield of the discs, as is shown by the yield of a transparent control disc of polystyrene, manufactured concurrently with No.'s 1 and 2. This disc gives a response under the standard gamma excitation only 0.03 times the reading of No. 1 which contains a comparable amount of plastic. (There remains the remote possibility that the polystyrene is excited to luminescence by the emission spectrum of the phosphor.)

#### 4.4. Recommendations for Future Work.

The visual radiation meter described in Chapter 3 is certainly realizable in its present form but is subject to



phenomenon to plastic mass flow is in the region of  $W = 3$  or higher, where the yield is sharply below that of the system, a characteristic shown by all three curves of Figure 6.4. Finally, inspection of disc No. 6 (No. 3 is a clear plastic control disc) with an optical microscope shows that the specimen, shown that it has a nearly constant grain size smaller than that of No. 3, but still polycrystalline. It is therefore unlikely that the attractive force of polymer on plastic at the top could be as or below optimum, and this is borne out by the brightness readings as shown.

The better performance of polystyrene in a disk, as compared to isotite, may be explained largely if not entirely by its higher level of orientation, more closely approximating that of the solid polymer. The polystyrene itself does not make an appreciable contribution to the light yield of the disk, as in wood's case yield of a transparent control disk of polystyrene, annealed and compressed to 0.1 and 0.2. This also gives a response most like that of the isotite control disk. 0.1 disk and control of No. 1 which contains a negligible amount of plastic. (These results are shown possibly that the polystyrene is not close to transparency by the critical spectrum of the photophor.)

#### 4.4. Interactions for Future Work.

The visual indicator water described in Chapter 3 is certainly feasible in its present form and is subject to



improvement in each of its components. Perhaps the most important uncertainties in the author's mind at present, so far as practical design considerations are concerned, are the optimum phosphor to eye distance and phosphor area, and the extent of possible improvement to be gained by viewing the two phosphors through a magnifying optical system. The maximum practical brightness from a mixture of phosphor and radio-active source material, and the rate of brightness decay as a result of continuous charged-particle bombardment should also be determined. The possibility of detecting other types of radiation with a visual instrument, and especially the detection of neutrons with plastic-phosphor discs deserve attention.

Although the objective of the work on phosphor-plastic mixtures, namely to obtain more usable light from a given amount of phosphor incorporated in such a mixture than could be obtained with the same mass of phosphor alone, has been attained to a degree which will be useful in the visual radiation meter, there are many directions in which further and probably greater improvements can be sought. A thorough search should be made for more efficient phosphors and for workable transparent plastics with higher refractive indices. In the absence of such plastics, experiments with liquids of high index might indicate what could be done if comparable plastics or other solid binders were available.

Improvement in each of the components. Perhaps the most important consideration in the author's mind at present, so far as practical design considerations are concerned, is the optimum proportion to the distance and angular area, and the extent of possible improvement to be gained by viewing the two phosphors through a carefully optical system. The various practical difficulties from a mixture of phosphor and radio-active source material, and the loss of balance between top and a source of continuous charged-particle bombardment should also be considered. The possibility of detecting other types of radiation with a visual instrument, and especially the detection of neutrons with plastic-phosphor lines deserve attention.

Although the objective of this work on phosphor-plastic mixtures, namely to obtain more usable light from a given amount of phosphor incorporated in such a mixture than could be obtained with the same mass of phosphor alone, has been attained to a degree which will be useful in the visual field of vision, there are many directions in which further and probably greater improvements can be sought. A thorough search should be made for more efficient phosphors and for workable transparent plastics with higher refractive indices. In the absence of such plastics, experiments with liquids or high index light indicators would be done if compatible plastics or other solid binders were available.

The individual curves of Figures 4.3-1 through 4.3-4 can be regarded as profiles of a three-dimensional surface which may be represented graphically if light yield is plotted along the z-axis, and the x- and y-axes are scaled in grams per square centimeter of plastic and phosphor respectively. Straight lines in the x-y plane, passing through the origin, then represent lines of constant phosphor/plastic ratio. Systematic exploration of such a surface for a given phosphor-plastic system, plotting contours of constant light yield, might lead to a fuller understanding of the effects of mixing plastic with phosphor.



The individual curves of Figure 4.7-1 through 4.7-4 can be regarded as profiles of a three-dimensional surface which may be represented graphically if it is plotted along the x-axis, and the y and z axes are scaled in units per square centimeter of plastic and phosphor respectively. Several lines in the x-y plane, passing through the origin, then represent lines of constant phosphor/plastic ratio. A systematic exploration of such a ratio for a given phosphor-plastic system, plotting against it constant light yield, might lead to a better understanding of the effects of mixing plastic with phosphor.

It is also possible to represent the light yield as a function of the plastic/plastic ratio.

Figure 4.7-5 shows the light yield as a function of the plastic/plastic ratio for a given phosphor-plastic system. The light yield is plotted against the plastic/plastic ratio, and the curve shows a maximum light yield at a plastic/plastic ratio of approximately 1.0. The light yield decreases as the plastic/plastic ratio increases or decreases from this maximum value. The curve is smooth and continuous, indicating a good fit to the experimental data. The light yield is measured in units per square centimeter of plastic and phosphor respectively. The plastic/plastic ratio is defined as the ratio of the plastic to the phosphor in the mixture. The curve shows that the light yield is maximized when the plastic and phosphor are mixed in a 1:1 ratio.

## APPENDIX A.1

### PHOTOMULTIPLIER CALIBRATION

In order to evaluate the visual effect of the light yield from phosphors without subjecting the experimenter to unnecessary radiation dosage, it became desirable to translate the 5819 photomultiplier anode current response to luminescence into a unit of brightness. The means of accomplishing this is as indicated in Figure A.1-1. The phosphor, excited by ultra-violet light, was viewed first by two observers using the Low-Brightness Meter, and then by the photomultiplier, as phosphor excitation was varied by interposing increasing thicknesses of U-V absorbing glass plates.<sup>1</sup> As shown in the figure, phosphor brightness and photomultiplier current are proportional as intensity of excitation varies over a range of 200 times the lowest brightness at which reliable readings could be made with the Low-Brightness Meter. The proportionality factor thus obtained ( $1.5 \times 10^{-5}$  foot-lamberts per micro-ampere) applies, of course, only to the particular emission spectrum (that of Zn-CdS(Cu) ), size of phosphor (1 7/16 in. ), and photomultiplier tube used in the calibration.

---

1. The application of the absorber technique to this problem was suggested by Professor Clark Goodman.

APPENDIX A-1

PHOSPHOR LUMINESCENCE CALIBRATION

In order to evaluate the visual effect of the light  
field from phosphor without subjecting the experimenter  
to unnecessary radiation dosage, it seems desirable to  
translate the 5519 phosphor multiplier scale output response  
to luminance into a scale of brightness. The means of  
accomplishing this is as indicated in Figure A-1-1. The  
photograph, excited by ultra-violet light, was viewed first  
by the observer using the low-brightness meter, and then  
by the photomultiplier, as phosphor excitation was varied  
of increasing increasing thicknesses of U-V absorbing  
glass plates.<sup>1</sup> As shown in the figure, phosphor brightness  
and photomultiplier current are proportional as intensity  
of excitation varies over a range of 100 times the lowest  
brightness at which reliable readings could be made with the  
low-brightness meter. The proportionality factor thus ob-  
tained ( $1.5 \times 10^{-3}$  foot-lamberts per micro-ampere) applies,  
of course, only to the particular emission spectrum (that  
of Zn-CdS(00)) ; size of phosphor (1/16 in.), and phos-  
multiplier tube used in the calibration.

1. The application of the multiplier constant to this prop-  
ion was suggested by Professor Clark Goodman.



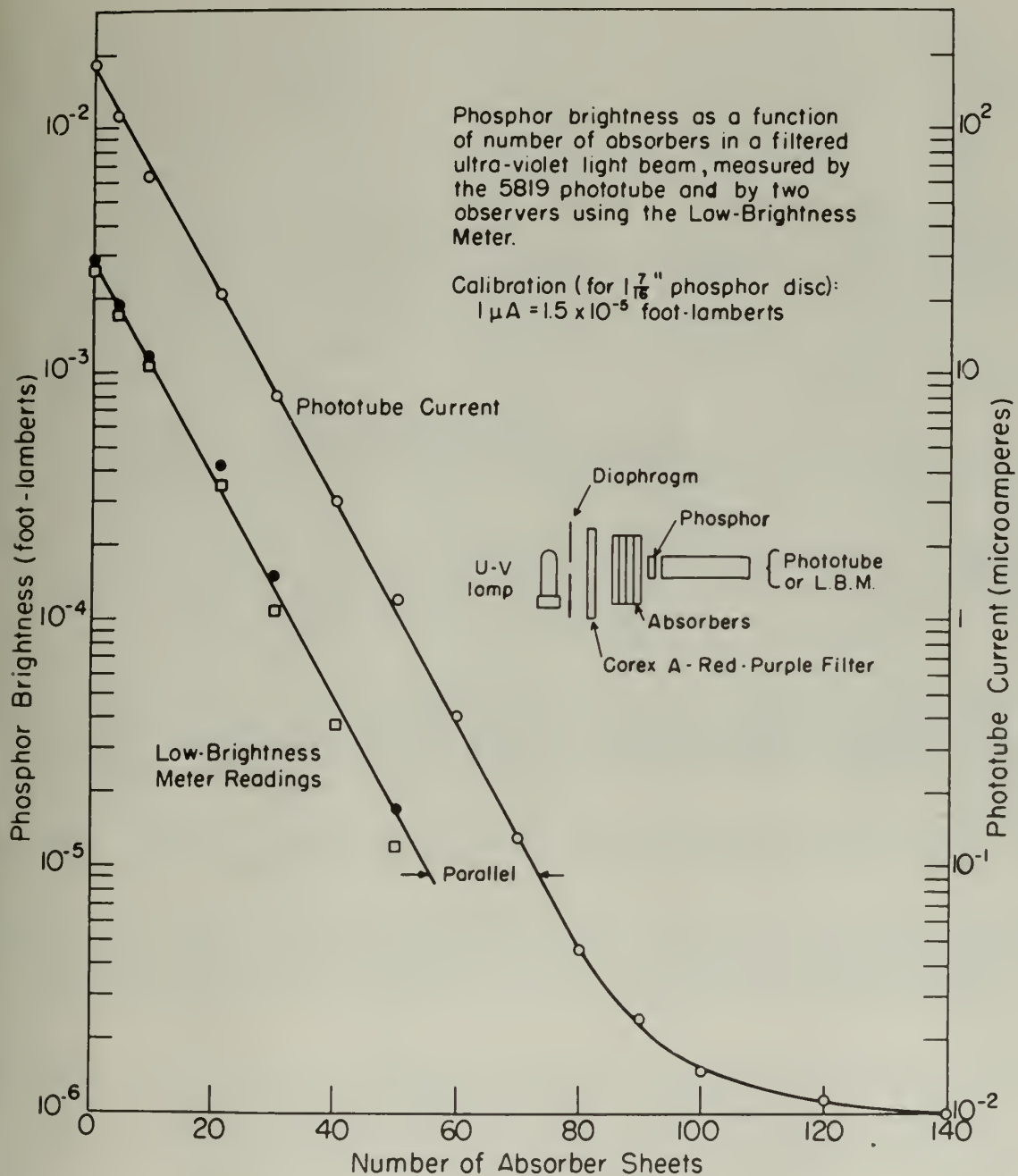


Figure A.1-1 PHOTOTUBE CALIBRATION



APPENDIX A.2

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APPENDIX A.3

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The Low Brightness Meter was made available through the cooperation of Messrs. Ray Smart and Russell Chen of

APPENDIX A

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The Low Lightroom Water was made available through the cooperation of Messrs. Ray Hunt and Russell Dunn of



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OEN/CO) and 10/10, were obtained by Mr. H.O. Gardner  
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The district assignment of Mrs. Knapp and the  
secretary work of Mrs. Knapp. This woman was previously so-  
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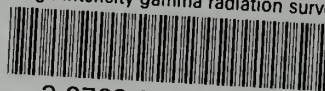
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